MATERNAL HYPERTENSIVE DISORDERS IN PREGNANCY AND MATERNAL MORBIDITY AT DELIVERY AND POSTPARTUM

by
Elizabeth Marilyn Harvey, MPH

A dissertation submitted to Johns Hopkins University in conformity with the requirements for the degree of Doctor of Philosophy

Baltimore, Maryland

December 2016

Abstract

Background: Rates of hypertensive disorders and other chronic conditions in pregnancy are increasing among childbearing women in the United States. This study examined the relation of maternal hypertensive disorders and other chronic and pregnancy-associated conditions with severe maternal morbidity (SMM) at delivery and postpartum rehospitalization.

Methods: Birth certificates and fetal death records (BCFD) were linked to delivery-related hospital discharge (HDD) records in Massachusetts from 2000-2012, using the Pregnancy to Early Life Longitudinal (PELL) data system (n=960,982). Non-injury emergency department (ED), observational stay (OS) and non-delivery hospital discharge (HD) records in the first year postpartum also were linked to corresponding BCFD and HDD deliveries from 2002-2011 (n=735,576); a subset of deliveries to women without chronic medical conditions were also examined (n=685,228). Multivariate logistic regression models estimated the odds of SMM at delivery, multivariate log-binomial and Poisson models estimated the risk of rehospitalization within six weeks and one year postpartum; analyses used a generalized estimating equations approach to account for correlation due to repeat births of women and adjusted for social and biological characteristics. Analyses also examined whether SMM modified the relation between hypertensive disorders and rehospitalization.

Results: Between 2000-2012, maternal hypertensive disorders were documented in 8.7% of deliveries and the SMM rate was 101.9 per 10,000 deliveries; 5.2% of deliveries from 2002-2011 had at least one rehospitalization within six weeks and 19.9% within one year

postpartum. Hypertensive disorders and other chronic conditions increased the odds of SMM and the risk of rehospitalization up to one year postpartum; this risk varied by type of hypertensive disorder. SMM at delivery independently increased rehospitalization risk in the first six weeks and year postpartum and slightly moderated the relation between hypertensive disorders and rehospitalization.

Conclusions: Maternal hypertensive disorders and other chronic conditions were associated with adverse maternal health outcomes at and after delivery and SMM at delivery was associated with increased risk of rehospitalization within one year postpartum. Our study highlights the need to prevent and manage hypertensive disorders and other chronic and pregnancy-associated conditions before, during, and after pregnancy as well as the need to address preventable SMM and mitigate its impacts after delivery.

Advisor: Dr. Donna Strobino, Ph.D.

Funding: This research was supported by the Maternal and Child Health Epidemiology Training Grant and the Centers of Excellence in Maternal and Child Health from the Maternal and Child Health Bureau (MCHB), Health Resources and Services Administration (HRSA) at the Department of Health and Human Services (DHHS).

Committee of Thesis Readers

Committee Members	Department
Kala Visvanathan Professor and Chair	Epidemiology
Donna Strobino Professor and Thesis Advisor	Population, Family and Reproductive Health
Saifuddin Ahmed Professor	Population, Family and Reproductive Health
Cynthia Argani Assistant Professor	School of Medicine Gynecology and Obstetrics

Alternate Committee Members

Andreea Creanga Assistant Professor	International Health
M.E. Hughes Associate Scientist	Population, Family and Reproductive Health
Pamela Surkan Associate Professor	International Health

Acknowledgements

I am extremely grateful for the support I have received to complete this dissertation. First, I would like to thank my advisor Dr. Donna Strobino for her invaluable guidance and support, both professionally and personally, throughout this process. I am also very appreciative of the other members of my committee: Drs. Kala Visvanathan, Saifuddin Ahmed, and Cynthia Argani as well as alternate committee members: Drs. Pamela Surkan, Andreea Creanga, and ME Hughes for their thoughtful insights and review of my work.

I am thankful for my colleagues in the Bureau of Family Health and Nutrition at the Massachusetts Department of Public Health. Drs. Susan Manning and Hafsatou Diop have been instrumental in this project and I appreciate their continued guidance to translate this research. Also, I am grateful to Karin Downs, an incredible supervisor, who has helped me find balance in my doctoral studies and work at the Department.

My family and friends have helped me find both strength and humor during this process. Thank you to my family—my husband, parents, sister, brother-in-law, aunts and uncles—for your unwavering confidence in me. Your love and endless supply of encouraging pep talks have kept me motivated and determined to complete this project. And, thank you to my brilliant cohort in the Department of Population, Family and Reproductive Health; I could not imagine this journey without you.

Also, I am very grateful to the Health Resources Services Administration's (HRSA) Maternal and Child Health Bureau for funding this work through the Maternal and Child Health (MCH) Epidemiology Training Fellowship and MCH Training Grant.

Table of Contents

List of Tables

Chapter Two: Literature Review and Conceptual Framework

Chapter Three: Research Design and Methods

Chapter Four: Results

List of Figures

Chapter Two: Literature Review and Conceptual Framework

Chapter Four: Results

Chapter One: Background and Specific Aims

Introduction

There are nearly four million births each year in the United States (1). With the vast majority of these births in hospitals, childbirth is the most frequent reason for hospital admission of females (2). Recent estimates suggest 600-800 women die from pregnancy and childbirth each year and another 65,000 experience severe morbidity (3, 4). Changing demographic characteristics of the childbearing population in the US suggest there are increasing proportions of women with high-risk pregnancies, including those of advanced maternal age and with chronic medical conditions such as hypertension, diabetes and asthma (1, 5).

Maternal health and chronic conditions represent research areas that are in alignment with Healthy People 2020 (HP2020) objectives related to reducing maternal mortality (MICH-5) and maternal illness and complications due to pregnancy (MICH-6) (6). Recent national research efforts to assess maternal health and wellbeing include defining and evaluating the prevalence of severe maternal morbidity (SMM) among US women at delivery; SMM in particular captures indications of organ-system failure indicative of severe events (3, 7). Yet there remain few national benchmark measures of maternal wellbeing after delivery. Surveillance of maternal health and morbidity before and after delivery is critical to improving women's health, particularly among women at risk.

In 2015, the Maternal and Child Health Bureau (MCHB) at the Health Resources and Services Administration (HRSA) announced the Maternal Health Initiative (MHI), a public-private partnership, with the overarching goal "to reduce maternal morbidity and

mortality by improving women's health across the life course, and by assuring the quality and safety of maternity care" (8). Of the five main areas proposed to improve maternal health in the US, one was improving surveillance and research, which included both determining the risk of severe morbidity and monitoring the impact of adverse outcomes on long-term maternal health (8). In addition, national efforts by the Centers for Disease Control and Prevention (CDC) and the American College of Obstetricians and Gynecologists recently called for routine standardized identification and evaluation of SMM cases by every birthing center in the US. (9-11). Understanding the causes and consequences of SMM is an emergent national research priority.

The primary goal of this dissertation is to examine how underlying maternal health status relates to morbidity both at delivery and into the first year postpartum. We used the Massachusetts Pregnancy to Early Life Longitudinal (PELL) data system from 2000-2012, which links vital records to hospitalization data, to examine the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions and maternal morbidity both at delivery and within the first year postpartum. The three specific aims of this dissertation were to:

Aim 1: Evaluate the relation of maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with severe maternal morbidity at delivery;

Aim 2: Evaluate the relation between severe maternal morbidity at delivery and postpartum maternal rehospitalization in the year following delivery among women without chronic medical diseases; and

Aim 3: Evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with postpartum maternal rehospitalization in the year following delivery independent of severe maternal morbidity at delivery.

Background

Rates of chronic conditions, including hypertensive disorders, are increasing among women giving birth in the United States. The prevalence of hypertensive disorders at delivery hospitalization among US women increased from 6.7% in 1998 to 8.3% in 2006 (12). In addition to hypertensive disorders, increasing trends were noted from 1999 to 2005 among California women presenting at childbirth with both preexisting and pregnancy-related comorbidities, including pre-existing and gestational diabetes, substance use, mental health conditions, and inflammatory conditions such as asthma, and thyroid disorders (13). The magnitude and increasing trend of maternal hypertensive disorders in pregnancy and other chronic and pregnancy-associated conditions warrant further understanding of their immediate sequelae at birth and in the postpartum.

The CDC estimated the rate of SMM to be 162.8 per 10,000 delivery hospitalizations during 2010-2011, an increase of 120% from 1998-1999, based on data from the Nationwide Inpatient Sample (14). Research studies of maternal morbidity at the national and state level have also examined the CDC classification and categorization of SMM (3, 15, 16). The economic burden of SMM is high; in an analysis of New York City deliveries from 2008-2012, SMM deliveries cost on average $15,714 compared to $9,357 for non-SMM deliveries (17). The impact of SMM after delivery into the first

year postpartum is unknown. The small, yet growing, burden of SMM in the US demands research both into its risk factors and consequences.

A better understanding of the relation between maternal hypertensive disorders and morbidity at delivery and in the postpartum is needed, especially in the context of national initiatives to improve maternal health. Limited research has examined more immediate adverse postpartum maternal outcomes of women; the rarity of clinical events related to SMM makes it difficult to obtain adequate data for research. Previous studies of postpartum maternal outcomes both in the US and globally also have faced limitations in their ability to control for important confounding variables such as behaviors like smoking (18-20), have not considered the impact of pre-existing conditions on outcomes (21, 22) and have focused on subpopulations that are not generalizable to the larger population (23, 24). A more in-depth look at hypertensive disorders and morbidity is needed at a population-based level with a greater ability to control for potentially confounding variables. This study investigated the relation between maternal health and morbidity before pregnancy, at delivery, and beyond the traditional postpartum period at a population-level.

The study results may inform prevention and management strategies at the state, facility and provider levels. At the state level, this research will inform the Massachusetts Perinatal Quality Collaborative (MPQC), which aims to improve maternal health outcomes through continuous quality improvement projects and the implementation of the maternal safety bundles (25, 26). This study may also provide a context for encouraging facilities to engage in the review of SMM cases, as called for by national organizations (10, 27). Further, this study also may reinforce the evidence-based

literature about the need of providers to address prevention and management strategies for hypertensive disorders to improve patient health before, during and after pregnancy. Beyond the implications of this particular research, the study highlights the usage of linked data systems to inform maternal health research at and after delivery.

Dissertation Overview

The dissertation is presented in five chapters. This chapter discussed the background for the study aims. The second chapter presents a literature review and a study rationale, followed by the conceptual framework that guided the research. The third chapter presents the methodological approach of this research, including the study design, data sources, dependent and independent variables, and analytic plan. Chapter four presents the results of the data analysis, including descriptions of univariate, bivariate, and multivariate results as well as sensitivity analyses. Chapter five concludes this dissertation, with a discussion of the main findings of each aim, the strengths and limitations of this research, followed by the public health implications and conclusions.

References

1. Hamilton BE, Martin JA, Ventura SJ. Births: preliminary data for 2012. Natl Vital Stat Rep. 2013;62(3):1-20. Epub 2013/12/11.

2. Eaton AP. Early postpartum discharge: recommendations from a preliminary report to Congress. Pediatrics. 2001;107(2):400-3. Epub 2001/02/07.

3. Callaghan WM, Creanga AA, Kuklina EV. Severe maternal morbidity among delivery and postpartum hospitalizations in the United States. Obstet Gynecol. 2012;120(5):1029-36. Epub 2012/10/24.

4. Creanga AA, Berg CJ, Ko JY, Farr SL, Tong VT, Bruce FC, et al. Maternal mortality and morbidity in the United States: where are we now? J Womens Health (Larchmt). 2014;23(1):3-9. Epub 2014/01/05.

5. Xaverius PK, Salas J. Surveillance of preconception health indicators in behavioral risk factor surveillance system: emerging trends in the 21st century. J Womens Health (Larchmt). 2013;22(3):203-9. Epub 2013/02/23.

6. Healthy People 2020. Washington, DC: U.S Department of Health and Human Services. Office of Disease Prevention and Health Promotion.

7. Callaghan WM, Mackay AP, Berg CJ. Identification of severe maternal morbidity during delivery hospitalizations, United States, 1991-2003. Am J Obstet Gynecol. 2008;199(2):133 e1-8. Epub 2008/02/19.

8. Lu MC, Highsmith K, de la Cruz D, Atrash HK. Putting the "M" back in the Maternal and Child Health Bureau: reducing maternal mortality and morbidity. Matern Child Health J. 2015;19(7):1435-9. Epub 2015/01/30.

9. Kilpatrick SJ, Berg C, Bernstein P, Bingham D, Delgado A, Callaghan WM, et al. Standardized severe maternal morbidity review: rationale and process. Obstet Gynecol. 2014;124(2 Pt 1):361-6. Epub 2014/07/09.

10. Callaghan WM, Grobman WA, Kilpatrick SJ, Main EK, D'Alton M. Facility-based identification of women with severe maternal morbidity: it is time to start. Obstet Gynecol. 2014;123(5):978-81. Epub 2014/05/03.

11. Kilpatrick SK, Ecker JL. Severe maternal morbidity: screening and review. Am J Obstet Gynecol. 2016;215(3):B17-22. Epub 2016/08/26.

12. Kuklina EV, Ayala C, Callaghan WM. Hypertensive disorders and severe obstetric morbidity in the United States. Obstet Gynecol. 2009;113(6):1299-306. Epub 2009/05/23.

13. Fridman M, Korst LM, Chow J, Lawton E, Mitchell C, Gregory KD. Trends in maternal morbidity before and during pregnancy in California. Am J Public Health. 2014;104 Suppl 1:S49-57. Epub 2013/12/21.

14. Severe Maternal Morbidity in the United States. Center for Disease Control and Prevention; [updated September 22, 2015; cited 2016 March 18]; Available from: http://www.cdc.gov/reproductivehealth/maternalinfanthealth/severematernalmorbidity.html.

15. Lyndon A, Lee HC, Gilbert WM, Gould JB, Lee KA. Maternal morbidity during childbirth hospitalization in California. J Matern Fetal Neonatal Med. 2012;25(12):2529-35. Epub 2012/07/12.

16. Gray KE, Wallace ER, Nelson KR, Reed SD, Schiff MA. Population-based study of risk factors for severe maternal morbidity. Paediatr Perinat Epidemiol. 2012;26(6):506-14. Epub 2012/10/16.

17. New York City Department of Health and Mental Hygiene. Severe Maternal Morbidity in New York City, 2008-2012. New York, NY. 2016.

18. Lykke JA, Langhoff-Roos J, Sibai BM, Funai EF, Triche EW, Paidas MJ. Hypertensive pregnancy disorders and subsequent cardiovascular morbidity and type 2 diabetes mellitus in the mother. Hypertension. 2009;53(6):944-51. Epub 2009/05/13.

19. Ray JG, Vermeulen MJ, Schull MJ, Redelmeier DA. Cardiovascular health after maternal placental syndromes (CHAMPS): population-based retrospective cohort study. Lancet. 2005;366(9499):1797-803. Epub 2005/11/22.

20. Irgens HU, Reisaeter L, Irgens LM, Lie RT. Long term mortality of mothers and fathers after pre-eclampsia: population based cohort study. BMJ. 2001;323(7323):1213-7. Epub 2001/11/24.

21. Kestenbaum B, Seliger SL, Easterling TR, Gillen DL, Critchlow CW, Stehman-Breen CO, et al. Cardiovascular and thromboembolic events following hypertensive pregnancy. Am J Kidney Dis. 2003;42(5):982-9. Epub 2003/10/29.

22. Savitz DA, Danilack VA, Elston B, Lipkind HS. Pregnancy-induced hypertension and diabetes and the risk of cardiovascular disease, stroke, and diabetes hospitalization in the year following delivery. Am J Epidemiol. 2014;180(1):41-4. Epub 2014/06/01.

23. Haas JS, McCormick MC. Hospital use and health status of women during the 5 years following the birth of a premature, low-birthweight infant. Am J Public Health. 1997;87(7):1151-5. Epub 1997/07/01.

24. Donahue D, Brooten D, Roncoli M, Arnold L, Knapp H, Borucki L, et al. Acute care visits and rehospitalization in women and infants after cesarean birth. J Perinatol. 1994;14(1):36-40. Epub 1994/01/01.

25. Henderson ZT, Suchdev DB, Abe K, Johnston EO, Callaghan WM. Perinatal quality collaboratives: improving care for mothers and infants. J Womens Health (Larchmt). 2014;23(5):368-72. Epub 2014/03/25.

26. D'Alton ME, Main EK, Menard MK, Levy BS. The National Partnership for Maternal Safety. Obstet Gynecol. 2014;123(5):973-7. Epub 2014/05/03.

27. Obstetric Care Consensus No 5 Summary: Severe Maternal Morbidity: Screening And Review. Obstet Gynecol. 2016;128(3):670-1. Epub 2016/08/23.

Chapter Two: Literature Review and Conceptual Framework

Overview

This chapter provides a review of the literature on maternal hypertensive disorders in pregnancy and maternal morbidity. The definition and classification of maternal hypertensive disorders are first reviewed, followed by their etiology, risk factors and recent trends. Other maternal chronic and pregnancy-associated conditions are briefly discussed, including a review of trend data. Next, the international context of maternal morbidity is presented along with a definition of severe maternal morbidity in the United States, followed by current trend information. Research on hypertensive disorders, maternal morbidity at delivery and postpartum maternal morbidity is discussed. The chapter presents a rationale for this research, including a review of limitations faced by previous studies, and concludes with a conceptual framework guiding the research.

Maternal hypertensive disorders

Definitions and classification

Maternal hypertensive disorders during pregnancy are classified by timing, onset and severity. Hypertension is defined as either systolic blood pressure (BP) of 140mm Hg or greater, a diastolic BP of 90 mm Hg or greater, or both (1). During pregnancy, chronic hypertension is defined as high blood pressure prior to conception or before twenty weeks gestation. Gestational hypertension is new onset high BP after twenty weeks gestation. Hypertension may also be stratified into mild and severe categories, with mild hypertension defined as systolic between 140-159mm Hg and/or diastolic 90-109mm Hg and severe as systolic greater or equal to 160mm Hg and/or diastolic greater or equal to 110mm Hg.

Preeclampsia is the most common form of high blood pressure that complicates

pregnancy. It is generally defined as the occurrence of new-onset hypertension and new-onset proteinuria (protein to creatinine ratio measures or exceeds 3.0 mg/dL) or other multi-systemic signs after twenty weeks gestation (1). In the absence of proteinuria, preeclampsia can be classified by the presence of hypertension with end organ complications characterized by one or more of the following: thrombocyptopenia, impaired liver function, renal insufficiency, pulmonary edema, or cerebral or visual disturbances (1). Superimposed preeclampsia is the new-onset of proteinuria or organ dysfunction after twenty weeks among women with chronic hypertension. Preeclampsia may be considered mild or severe in accordance with the blood pressure measurement. In addition, preeclampsia is often categorized as early-onset, occurring earlier than 34 weeks gestation or late onset, after 34 weeks gestation.

Etiology and risk factors

While the pathways that lead to preeclampsia and eclampsia are unknown, current hypotheses suggest that the disorder is the result of disturbed placental function early in pregnancy. There may be poor uterine vasculature, reducing placental perfusion, which in turn may lead to unbalanced transfer of nutrients and oxygen to the fetus and carbon dioxide and waste to the maternal blood supply (2). Resulting placental hypoxia is hypothesized to trigger the placenta to release proinflammatory cytokines into circulation that damage the endothelium, a thin membrane lining the inside of heart and blood vessels, and ultimately result in manifestation of the maternal syndrome of preeclampsia (2-4).

It is hypothesized that early onset preeclampsia, which compromises 5-20% of preeclampsia cases and occurs before 34 weeks gestation, has a different etiology than

later onset preeclampsia (4). In addition to different pathologies of early and late onset preeclampsia, the National Institute of Child Health and Human Development (NICHD) workshop on preeclampsia in 2006 suggested that pathologies associated with preeclampsia differed for nulliparous and parous women (2). The NICHD workshop acknowledged the "complex and multifactorial nature" of preeclampsia and suggested that it is a condition of excessive systemic inflammation (2).

The theory of excessive systemic inflammation in the manifestation of preeclampsia also raises the potential role of other inflammatory chronic conditions during pregnancy on maternal morbidity, including asthma and autoimmune diseases. In a recent meta-analysis, mothers with asthma had an increased risk of preeclampsia compared to mothers without asthma (Relative Risk: 1.54) (5). One mechanism proposes that acute asthma exacerbations cause maternal hypoxemia, low oxygen in the maternal blood, leading to fetal hypoxia; with limited blood flow to the fetus, fetal growth restriction or uteroplacental insufficiency may result (6). Autoimmune diseases, such as lupus erythematosus and multiple sclerosis, also involve chronic inflammatory states. Preeclampsia may complicate 13-35% of pregnancies to women with systemic lupus erythematosus (7). For pregnant women with either multiple sclerosis or systemic lupus erythematosus, there are increased serum levels of proinflammatory cytokines in comparison to women without the disease (8, 9). The origins and pathways of other systemic inflammatory responses in chronic conditions similar to hypertensive disorders in pregnancy are also important to explore.

Researchers have identified some factors associated with a higher risk of developing preeclampsia and eclampsia. The American College of Obstetrics and

Gynecology (ACOG) in its most recent report on Hypertension in Pregnancy lists the following risk factors for preeclampsia: primiparity, previous preeclamptic pregnancy, chronic hypertension or chronic renal disease, history of thrombophilia, multifetal pregnancy, in vitro fertilization, family history of preeclampsia, type 1 or type 2 diabetes, obesity, systemic lupus erythematosus, and advanced maternal age greater than 40 years (1). A systematic review by Duckitt et al. (2005) showed the strongest risk factors for preeclampsia to be among women with: antiphospholipid syndrome (RR 9.72), previous history of preeclampsia (RR 7.19), and type 1 diabetes (RR 3.56) along with multiple pregnancy, family history, high body mass index, and maternal age (10).

Racial, ethnic, and socioeconomic differences have also been reported for hypertensive disorders during pregnancy in the US. Results of a population-based study in California using linked vital statistics and hospital discharge data showed Hispanic and non-Hispanic black women had slightly higher odds of gestational hypertension and chronic hypertension than non-Hispanic white women after adjustment for age, parity, education, insurance status, prenatal care adequacy, and route of delivery (11). Other studies in New York State showed that rates of all hypertensive disorders during pregnancy were highest among non-Hispanic black women across all regions and poverty levels (12, 13). Tanaka et al. (2007) observed increasing racial and ethnic disparities in hypertension rates even after stratification by socioeconomic status and other risk factors over a 10-year population-based study of merged hospital discharge and census data in New York State (12). In a population-based study of singleton live birth deliveries using linked hospital discharge and birth certificate data over 10 years in New York State, Savitz et al. (2014) found black women had higher odds of all hypertensive disorders,

after adjusting for year, age, insurance, and urban/rural county.

A European population-based prospective cohort study suggested women with low education had almost five times the odds of preeclampsia than women with high education, adjusted for: age, gravidity, multiple pregnancy, financial difficulties, smoking in pregnancy, working conditions, body mass index and blood pressure at enrollment (14). These disparate rates of hypertensive disorders during pregnancy by race and ethnicity and socioeconomic status suggest the need to account for these variables in research on the relation of hypertensive disorders with severe maternal morbidity.

Prevalence and trends

Rates of hypertensive disorders during pregnancy appear to be rising in the US. The prevalence of hypertensive disorders in delivery hospitalizations (inclusive of chronic and gestational hypertension, and mild and severe preeclampsia/eclampsia) increased from 6.7% in 1998 to 8.3% in 2006 in the US; all subtypes showed increasing trends except mild preeclampsia (15). In Massachusetts, data from 1998-2007 suggested 7.0% of women giving birth had pregnancy-related hypertension, defined as gestational hypertension, preeclampsia, or eclampsia (16).

Other national data from 2001-2005 suggest the most common obstetric complication was preeclampsia/eclampsia, which affected 3.4% of deliveries, an 11% increase from 1993-97 to 2001-05 (17). Massachusetts data from 1998-2007 indicated a similar overall preeclampsia prevalence of 3.3%, with 0.6% of preeclampsia cases occurring prior to 34 weeks (16).

There also appear to have been increases in gestational and chronic hypertension.

National data indicate an increase in gestational hypertension among delivery hospitalizations from 2.1% in 1993-97 to 3.1% in 2001-05 (17). An increase was also noted based on linked birth certificate and hospital discharge data in California from 4.4% to 4.9% between 1999 and 2005, figures higher than national data (11). Chronic hypertension varied from less than 1% to almost 2% in recent studies; a 2014 New York State study estimated chronic hypertension prevalence to be 0.83% (13) while research using the National Inpatient Database reported a prevalence of 1.8% in 2007-08, an 80% increase over the 14-year study period (18). Data from the National Hospital Discharge Survey corroborate this finding, reporting that chronic hypertension affected 1.9% of delivery hospitalizations and was 24% higher in 2001-05 than in 1993-97 (17). Data from California documented a 47.5% increase in chronic hypertension from 0.63% to 0.93% between 1999 and 2005 (11). Super-imposed preeclampsia is the rarest of all hypertensive disorders in pregnancy: researchers examining data from New York State recently estimated it to impact 0.23% of pregnant women (13).

Some of the increasing rates of hypertensive disorders may be reflective of changing trends in the childbearing population as women are presenting at childbirth with an increasing number of both preexisting and pregnancy-related comorbidities. Over the past two decades, birth rates in the US decreased for women aged 15-29 years and increased for older women aged 35-44 years, especially for women 40 years and older (from 1.2% of all births in 1990 to 2.9% in 2010) (19). Maternal chronic conditions increase with age: researchers showed increased odds of both chronic hypertension and superimposed preeclampsia among women 35 years and older during delivery hospitalization in New York compared to women 25-29 years (13). Additionally, pre-

pregnancy obesity has risen in the past two decades (20, 21). Among nine states with available data, there was a 69% increase in pre-pregnancy obesity from 13% in 1993 to 22% in 2002 (21). Even though adjusted analyses suggest increases in hypertensive disorders independent of maternal risk factors (11), better ascertainment of disease may also be reflected in this increase.

Other maternal chronic and pregnancy-associated conditions

Prevalence and trends

Rates of other chronic and pregnancy-associated conditions also appear to be increasing among pregnant women in the US. In the National Discharge Survey, the rate of asthma during hospital delivery almost doubled from 0.7% during the period 1993-1997 to 1.3% during the period 2001-2005 (17). In the National Inpatient Sample, the rate of depression at hospital delivery increased from 0.3% to 1.4% from 1998 to 2005 (22). In California, chronic disease rates increased significantly from 1999-2005, including: asthma (1.0% to 1.8%), substance abuse (1.7% to 2.9%), mental health conditions, including depression (1.0% to 1.2%), pre-existing diabetes (0.7% to 0.8%), and gestational diabetes (4.0% to 5.7%) (11).

Severe maternal morbidity at delivery

International context

Maternal morbidity and mortality can be considered on a continuum with major categories ranging from normal/healthy pregnancy, morbidity, severe morbidity, near miss, to death (23). In 2011, the World Health Organization (WHO) adopted the definition of maternal "near miss" as "a woman who nearly died but survived a

complication that occurred during pregnancy, childbirth or within 42 days of termination of pregnancy" and established standard criteria to examine quality of obstetric care (24). In 2010-2011, the WHO Multi-country Survey on Maternal and Newborn Health project included over 314,000 women and their infants in 29 countries to assess the management of severe maternal complications and the prevalence of maternal near miss, which was estimated to be 0.8% (25). This project also developed the maternal severity index (MSI), which estimates the probability of death in women with complications related to pregnancy. In 2016, the WHO Maternal Morbidity Working Group defined maternal morbidity and associated disability as "any health condition attributed to and/or complicating pregnancy and childbirth that has a negative impact on the woman's wellbeing and/or functioning" and proposed a standard matrix of 121 conditions for measurement (26). In part, this shift represents the recognition that the term "near miss" can be ambiguous because by definition it is a facility-based measure, not a population-based one (27).

US definition, classification and validation

The CDC defines maternal morbidity as encompassing "physical and psychologic conditions that result from or are aggravated by pregnancy and have an adverse effect on a woman's health" (28). Building on frameworks of antenatal hospitalizations (29, 30), complications during delivery hospitalization (31, 32) and international guidelines (24), the CDC developed an identification system to define severe maternal morbidity (SMM) based on the International Classification of Disease, 9th Revision, Clinical Modification (ICD-9-CM) diagnosis and procedure codes (33). This system of measuring SMM was updated and refined in 2012 to include a total of twenty-five specific ICD-9-CM codes

that capture indications of organ-system failure indicative of severe events (33, 34) (**Table 2.1**). Kuklina et al. (2009) refined the Callaghan et al. (2008) definition of SMM to classify the presence of SMM only among deliveries with a length of stay ≥90th percentile for mode of delivery; reclassification did not apply to procedure-based codes (35).

Table 2.1 Severe Maternal Morbidity Indicators

Severe Maternal Morbidity Indicator	ICD-9-CM Diagnosis Code	ICD-9-CM Procedure Code
1. Acute myocardial infarction	x	
2. Acute renal failure	x	
3. Adult respiratory distress syndrome	x	
4. Amniotic fluid embolism	x	
5. Aneurysm	x	
6. Cardiac arrest/ventricular fibrillation	x	
7. Disseminated intravascular coagulation	x	
8. Eclampsia	x	
9. Heart failure during procedure or surgery	x	
10. Internal injuries of thorax, abdomen, and pelvis	x	
11. Intracranial injuries	x	
12. Puerperal cerebrovascular disorders	x	
13. Pulmonary edema	x	
14. Severe anesthesia complications	x	
15. Sepsis	x	
16. Shock	x	
17. Sickle cell anemia with crisis	x	
18. Thrombotic embolism	x	
19. Blood transfusion		x
20. Cardio monitoring		x

21. Conversion of cardiac rhythm	x
22. Hysterectomy	x
23. Operations on heart and pericardium	x
24. Temporary tracheostomy	x
25. Ventilation	x

In 2016, the CDC SMM ICD-9-CM criteria were validated with chart reviews and found to have reasonably high sensitivity (0.77) and a positive predictive value (PPV) of 0.44 with a C-statistic of 0.87; researchers found the sole indicator of blood transfusion to be the most important source of false-positives. Main et al. (2016) concluded these criteria "can serve as a reasonable administrative metric for measuring severe maternal morbidity at population levels" but cautioned against the use of the criteria at individual hospitals because case-mix effects were strong (36). Another study analyzing the validity of SMM discharge billing codes found a range of PPVs for SMM categories, with an overall PPV of 89% (99% CI: 82%-93%) when length of stay was restricted to greater or equal to 3 days; researchers found "codes demonstrated a high PPV when supporting medical information contained objective data, such as laboratory values, pathology results, or procedure documentation" (37).

Prevalence and trends

The rate of SMM in the US was estimated to be 163 per 10,000 delivery hospitalizations in 2010-2011, an increase of 120% from 1998-1999 based on data from the Nationwide Inpatient Sample, the largest all-payer hospital inpatient care database in the US (38). Some researchers examining SMM at the national and state level have started to use the CDC classification and categorization while others have relied on other

markers of morbidity at delivery, including: admission to the ICU or blood transfusion greater than or equal to four units or prolonged postpartum length of stay (39). Findings from research into other risk factors for morbidity among US women at delivery show increased risk among women older than 35 years, of non-white race/ethnicity, with multiple gestations, and with a prior cesarean delivery (40-44). Recent research has also suggested women with singleton pregnancies conceived through assisted reproductive technology are at increased risk of SMM at delivery (45, 46).

Hypertensive disorders and maternal morbidity at delivery

Hypertensive disorders during pregnancy are associated with adverse maternal outcomes at delivery, although definitions of morbidity vary in these studies (15, 40, 41, 47-49). In a study of morbidity measured by obstetric-related ICU admissions, the leading diagnosis associated with admission was pregnancy-related hypertensive disease, present in 29.9% of admissions (49). Researchers using data from the Nationwide Inpatient Sample of the Healthcare Cost and Utilization Project found women with hypertensive disorders had increased risk of adverse outcomes including acute renal failure, pulmonary edema, adult respiratory disease syndrome, puerperal cerebrovascular disorder, disseminated intravascular coagulation syndrome, and ventilation (15); these specific outcomes represent some conditions and procedures included in the SMM definition. In an NICHD study of 25 Maternal-Fetal Medicine Unit Networks, women with any hypertension diagnosis had a greater than 3-fold increase in severe maternal morbidity, defined as a score-based system of ICU admissions, intubation greater than 12 hours, organ failure, surgical intervention, or blood transfusion greater than 3 units (40). Previous studies of hypertensive disorders have not specifically considered the CDC

definition of SMM as an outcome, and others have not adequately controlled for important confounding variables, especially other chronic comorbidities, limiting the validity of their inferences.

Conditions and procedures in the CDC classification system of SMM related to cardiovascular illness represent a plausible pathway of the manifestation of hypertensive disorders due to damage to the endothelium, the linings of the heart and blood vessels (2, 3). Plausible pathways are also suggested for a relation of hypertensive disorders with SMM for other conditions and procedures included in the measure. For example, considering women with preeclampsia, clinical decisions to deliver before full gestation increase the likelihood of cesarean delivery and may, in turn, increase the risk of sepsis or of anesthetic complications (50, 51). Additionally, preeclampsia may lead to increased risk of hemorrhage requiring transfusions, another qualifying procedure for SMM, due to decreased blood flow to organs other than the placenta (52). Another indicator of SMM is amniotic fluid embolism, which is hypothesized to be related to placental abnormalities (53).

Other chronic conditions also are associated with morbidity at delivery. A review of women with asthma found those with severe or poorly controlled asthma have an increased risk of spontaneous abortion, intrauterine growth restriction, preterm delivery, postpartum hemorrhage and cesarean delivery (6). In a retrospective cohort study of a over 280,000 pregnancies from a primary care database of women in England and Wales, women with asthma were at increased odds of postpartum hemorrhage, anemia and cesarean delivery after adjustment of maternal age, smoking habit, and body mass index (54). In a review of autoimmune conditions, among women with systemic lupus

erythematosus, there was a two- to four-fold higher rate of pregnancy complications, including preterm labor and cesarean delivery; among women with rheumatoid arthritis, there was an increased frequency of cesarean delivery (7). In a large population-based study in Sweden, women with type 1 diabetes had increased odds of cesarean delivery and very preterm birth, after controlling for maternal age, parity, body mass index, chronic hypertensive disease, smoking habits and ethnicity (55). In a systematic review and meta-analysis including 30 studies, maternal depression during pregnancy was associated with increased odds of premature delivery (56). And in a linked population-level administrative database study, women with illicit drug use in pregnancy, including opioids, stimulants, and cannabis, were more likely to deliver preterm after adjustment of maternal age, smoking, other drug use, ethnicity, and insurance status (57). Most of these studies assessed outcomes in the newborn, and few have specifically addressed maternal morbidity. The lack of research on maternal morbidity for these conditions is an important gap in the literature addressed by our study.

Maternal morbidity in the postpartum period

Traditionally, the first six weeks after delivery are considered the postpartum period. The American College of Obstetricians and Gynecologists recommends all women have a comprehensive postpartum visit within the first six weeks after birth (58). Complications occurring during this time are generally considered to be related to events during pregnancy or delivery (59). National surveys such as the National Inpatient Sample or the National Discharge Survey have attempted to capture postpartum maternal health through examining specific hospitalization inpatient codes, but these data are dependent on a postpartum hospitalization diagnosis coding (34, 35). While they can be

used to estimate maternal morbidity rates during the postpartum hospitalization, they are not linked to hospital delivery discharge data for individual women. On a population level, linkage of the birth certificate, hospital discharge delivery records, and prospective hospital utilization data after delivery to assess maternal health is undertaken at the state level (60-62). Massachusetts is one state in which this linkage has been undertaken.

An increased research focus on the impact of delivery hospitalization for both the mother and infant ensued when Health Maintenance Organizations and third party payers started to encourage shorter delivery stays in the 1990s (63). In general, a short stay for a vaginal delivery is considered less than 48 hours and less than 96 hours for a cesarean delivery (63). More recently, with the increased rate of cesarean deliveries in the US, researchers have investigated the impacts of short lengths of stay by method of delivery through maternal rehospitalization, generally defined as an admission to a hospital within a specified time of a discharge from the same or another hospital (62, 64, 65).

Liu et al. (2002) examined length of stay and maternal rehospitalization within 60 days among Canadian women, finding an increased risk of readmissions with short length of stay among women with cesarean deliveries; the most frequent risk factors and causes of readmission were postpartum hemorrhage, major puerperal infection and some hypertensive disorders (64). In a case control study, Sharvit et al. (2014) found increased risk of rehospitalization within 14 days associated with emergency cesarean delivery; the most common indication of rehospitalization was infection (65). The length of stay concept also led to research focused on discharge readiness, which addresses a more individualized approach taking into consideration the opinions of the mother, pediatrician and obstetrician for the timing of discharge; researchers found increased health care use

and poorer health outcomes 2-4 weeks post-delivery among mother-infant dyads when there was discordance in provider and patient opinions about discharge readiness (66).

Some researchers also have focused on specific populations to examine postpartum maternal health. Among a hospital network in the US, Clark et al. (2010) found that 4.8% of women who deliver were seen in the Emergency Department within 42 days of delivery (67). The results of a study of women delivering low birth weight (LBW) or preterm infants showed that almost 60% were rehospitalized within five years (68). Among women with a cesarean delivery, researchers found the most common major complication after delivery to be maternal infection, with infections in 29% of women during delivery hospitalization and 8% after primary hospital discharge (69).

Other studies of postpartum morbidity combine both pregnant women and postpartum women (<42 days post-delivery) to examine hospitalizations (34, 70). In a review of studies, pregnant and postpartum women accounted for 0.4-16% of all Intensive Care Unit admissions. Hypertensive disorders were the most prevalent indication for admissions (70).

Hypertensive disorders and postpartum morbidity

Preeclampsia is associated with poor long-term outcomes in women. In particular, meta-analyses have identified preeclampsia as a risk factor for later stage cardiovascular disease. McDonald et al. (2008) found women with preeclampsia/eclampsia had more than double the risk of subsequent cardiac disease, cerebrovascular disease, and cardiovascular mortality in a meta-analysis of fifteen studies, ten of which focused on women less than 56 years of age (71). Bellamy et al. (2007) found preeclampsia to be

related to increases in the risk of future hypertension, ischemic heart disease, venous thromboembolism, and death from any cause, with weighted mean follow-up for outcomes ranging from 4.7-14.5 years (72). This research supports a common cause of preeclampsia and cardiovascular disease, specific vascular damage due to preeclampsia, or both (72). Research into subclinical outcomes also indicate increased odds of higher blood pressure and being on blood pressure medication among women with a history of hypertensive disorders during pregnancy, with a mean follow-up time of 16.5 years (73). In 2011, the American Heart Association updated their clinical guidelines to include a history of preeclampsia or pregnancy-induced hypertension as risk factors for cardiovascular disease in women (74).

Some US studies examining associations between maternal hypertensive disorders during pregnancy and post-delivery maternal outcomes focused on specific vulnerable populations. Hamilton et al. (2002) examined postpartum hospitalization among women with high-risk pregnancies, a group including women diagnosed with chronic hypertension; they found that one in six women required one or more rehospitalization and almost one in five required an acute care visit within one year postpartum (75). Another study of only women with insurance found that those with hypertensive disorders during pregnancy were more likely than women without complications to attend primary care visits in the year after delivery; however, the rates of primary care utilization were still below what was recommended (76).

Other US studies face some methodological limitations. One large population-based study in the Washington State from 1998-2000 examined varying severity of hypertension during pregnancy and cardiovascular and thrombolytic events (60). A

greater than 2-fold risk for cardiovascular events was noted among women with gestational hypertension, and mild and severe preeclampsia. While the researchers combined records from birth certificate and hospital discharge data, and followed women for a median length of 8 years, they excluded chronic hypertension as an exposure. Another study found increased risk of prehypertension and hypertension in the early years after delivery among women who developed gestational hypertension; however, they only focused on women who had prenatal care and delivered live singleton neonates at one US medical center and did not have data about pre-existing hypertension (77). Another study examined the relation between preeclampsia and ischemic stroke among US women 15-44 years of age in a case control study but relied on self-reports by women of a physician diagnosis of preeclampsia (78).

One recent US study in New York City, using linked birth certificate data and hospital discharge data, examined more immediate clinical events among women with gestational hypertension and preeclampsia in the year following delivery (61). The researchers found increased odds of heart failure among women who had gestational hypertension during pregnancy and increased odds of heart failure, intracranial hemorrhage, stroke/transient ischemic attack, coronary heart disease, deep vein thrombosis, and type 2 diabetes among those with preeclampsia (61). Although Savitz et al. (2014) used hospital discharge data linked to birth certificate data, they did not also use the birth certificate to ascertain conditions during pregnancy, with the exception of gestational diabetes (61). Using both the birth certificate and hospital discharge data improves the ascertainment of conditions compared to using only one data source (79, 80). They also did not investigate women with chronic hypertension in the analysis (61).

Study Rationale

A life course perspective addressing pre-pregnancy conditions is important in understanding the impact of hypertensive disorders and other chronic and pregnancy-associated conditions. Previous research on the relation between hypertensive disorders and maternal morbidity has generally excluded women with pre-existing conditions, specifically chronic hypertension, limiting the generalizability of the research to women with underlying chronic conditions (60, 61). Some studies aggregated all pre-existing conditions, including hypertension, into one category, limiting the ability to understand the role of chronic hypertension specifically (42). The current study examined women with underlying chronic conditions that included maternal hypertensive disorders and other common chronic conditions such as pre-existing diabetes, asthma, autoimmune conditions, depression, and substance use disorders as well as pregnancy-associated conditions such as gestational diabetes.

In addition to examining chronic conditions prior to pregnancy, other indicators, considered as confounders, captured the context of a woman's social and biological environment. Prior birth outcomes as well as household and family characteristics may be critical in the relation between hypertensive disorders in pregnancy and maternal morbidity at and after delivery. Previous research has been limited by failure to adjust for the timing of delivery and socio-demographic variables, such as race/ethnicity and smoking (15). It also has been limited by data available largely for delivery events, and not for the women themselves (15, 33, 47, 81). This study examined deliveries to women from delivery through one year postpartum and linked repeat births as well as accounted for a range of social and biological variables obtained from multiple sources.

Research on maternal health in the US has been limited, in general, and studies following women after delivery are particularly sparse in number. Previous studies have not captured postpartum maternal health, with the exception of some case control studies within single institutions and studies of short time periods after delivery or among specific populations (75, 76). To address the limitation of short follow-up in previous research, this study examined postpartum maternal rehospitalization within six weeks and up to one year post-delivery to align with standard maternal and pregnancy-related mortality measures in the US (82). The ability to link surveillance systems from delivery into the postpartum period in Massachusetts offered avenues to explore these pathways more comprehensively, including three different measures of postpartum maternal morbidity: emergency department admissions, observational stays, and hospital discharge rehospitalizations.

The recent national efforts to define and explore SMM at delivery offered new opportunities to explore maternal health prior to and after delivery. It is unknown if hypertensive disorders in pregnancy or SMM at delivery are associated with maternal morbidity in the postpartum. Some studies have examined type of delivery and readmission rates but have not accounted for pre-existing or pregnancy-related conditions or the severity of maternal conditions at birth beyond type of delivery (62). Moreover, other studies that examined the relation between hypertensive disorders during pregnancy and postpartum maternal health did not take into account chronic maternal conditions preceding birth (61). This study investigated the relation between maternal health and morbidity before pregnancy, at delivery, and beyond the traditional postpartum period at a population-level.

Conceptual Framework

Based on the review of literature, the framework informing this study suggests the need for an integrative approach to examine women's health. The conceptual framework attempts to integrate biological, social, and biosocial pathways in understanding the relation between hypertensive disorders during pregnancy and morbidity at birth and in the postpartum. The conceptual framework adapts both a life course and an integrated perinatal health approach, centered on the premise that pregnancy is a critical period in a woman's life, affecting her future health. It acknowledges factors present prior to pregnancy, especially risk factors that may be shared among hypertensive disorders and cardiovascular disease (83). The model provides the basis for the methodological approach in this study.

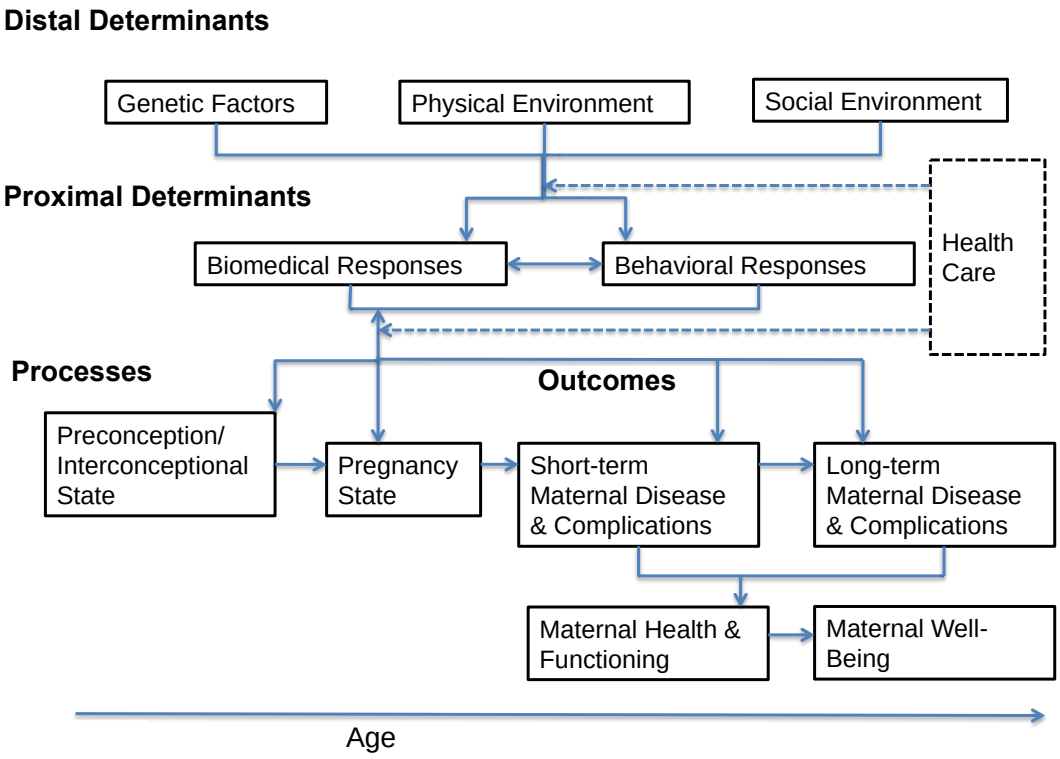
Ben-Shlomo and Kuh (2002) define a life course approach to chronic disease epidemiology as "the study of long-term effects on chronic disease risk of physical and social exposures during gestation, childhood, adolescence, young adulthood and later adult life" (84). The approach posits factors that either raise disease risk or promote good health accumulate gradually over the life course although there are critical periods where "an exposure can have adverse or protective effects on development and subsequent disease outcome." Pregnancy is considered a critical period of development for the fetus, but to a lesser extent, for the mother. Our work highlights the need to extend the model to women's health before, during and following pregnancy. Thus, we adapt the life course model to consider the impact of hypertensive disorders during pregnancy on SMM at the time of delivery as well on the subsequent health of the mother as measured by maternal hospitalization in the year postpartum.

The integrated perinatal health framework proposed by Misra, Guyer and Allston (2003) also recognizes the social, psychological, behavioral, environmental and biological influences prior to pregnancy that impact outcomes in addition to the changing demography of pregnancy with more women delaying their first birth (85). The conceptual framework is also informed by research suggesting women at high risk for cardiovascular disease may be identified during the reproductive years. Research has shown increased risk of cardiovascular disease among women with hypertensive disorders during pregnancy although the mechanisms linking pregnancy events to later life disease are not well understood (86-88).

Applying a women's health life course-based framework centered on the reproductive years, the conceptual model adapts the framework of Misra, Guyer and Allston (2003) to examine the health trajectories of women at birth and in the year following delivery in the context of distal and proximate determinants. Also informed by Ben-Sholmo and Kuh (2002), this conceptual model adapts their ideas to consider an integration of social and biological factors both prior to and during pregnancy for the mother (**Figure 2.1**).

Figure 2.1 Conceptual Framework

Maternal Health Conceptual Framework adapted from Misra, Guyer and Allston (2003)



In this framework, distal and proximate factors influence a woman's health before, during and after pregnancy. Distal factors consider genetic factors, and the physical and social environment. While it was not possible to consider genetic factors in the current study, the social environment includes individual characteristics, such as socioeconomic status and race, as well as partner, family, and neighborhood characteristics. Proximal risk factors acknowledge the interplay between biomedical responses, including chronic conditions, with behavioral responses, such as smoking. Distal and proximal factors influence a woman's health prior to conception, through pregnancy, birth and post-delivery. Short-term maternal disease and complications represent maternal morbidities at

birth, while long-term maternal disease and complications may include rehospitalizations within the first year postpartum.

The framework also includes health care as a modifying characteristic that may impact a variety of relations in the framework, from primary prevention activities to medical interventions. There are potential unknown factors in this conceptual model that require acknowledgement, as the etiology of hypertensive disorders during pregnancy is unknown. This study cannot evaluate all dimensions of framework described here but focuses on the periods during and after pregnancy, informed by prior and current biological and behavioral responses as well as health care and sociodemographic characteristics. Most importantly, the framework focuses on the health of the mother, not the fetus or newborn; it has generally not been considered in this context.

References

1. American College of Obstetricians and Gynecologists Task Force of Hypertension in Pregnancy. Hypertension in pregnancy. Washington, D.C.: 2013.

2. Ilekis JV, Reddy UM, Roberts JM. Preeclampsia--a pressing problem: an executive summary of a National Institute of Child Health and Human Development workshop. Reprod Sci. 2007;14(6):508-23. Epub 2007/10/26.

3. Steegers EA, von Dadelszen P, Duvekot JJ, Pijnenborg R. Pre-eclampsia. Lancet. 2010;376(9741):631-44. Epub 2010/07/06.

4. Madazli R, Yuksel MA, Imamoglu M, Tuten A, Oncul M, Aydin B, et al. Comparison of clinical and perinatal outcomes in early- and late-onset preeclampsia. Arch Gynecol Obstet. 2014;290(1):53-7. Epub 2014/02/20.

5. Murphy VE, Namazy JA, Powell H, Schatz M, Chambers C, Attia J, et al. A meta-analysis of adverse perinatal outcomes in women with asthma. BJOG. 2011;118(11):1314-23. Epub 2011/07/14.

6. Racusin DA, Fox KA, Ramin SM. Severe acute asthma. Semin Perinatol. 2013;37(4):234-45. Epub 2013/08/07.

7. Barbhaiya M, Bermas BL. Evaluation and management of systemic lupus erythematosus and rheumatoid arthritis during pregnancy. Clin Immunol. 2013;149(2):225-35. Epub 2013/06/19.

8. Baird SM, Dalton J. Multiple sclerosis in pregnancy. J Perinat Neonatal Nurs. 2013;27(3):232-41. Epub 2013/08/01.

9. Lateef A, Petri M. Management of pregnancy in systemic lupus erythematosus. Nat Rev Rheumatol. 2012;8(12):710-8. Epub 2012/08/22.

10. Duckitt K, Harrington D. Risk factors for pre-eclampsia at antenatal booking: systematic review of controlled studies. BMJ. 2005;330(7491):565. Epub 2005/03/04.

11. Fridman M, Korst LM, Chow J, Lawton E, Mitchell C, Gregory KD. Trends in maternal morbidity before and during pregnancy in California. Am J Public Health. 2014;104 Suppl 1:S49-57. Epub 2013/12/21.

12. Tanaka M, Jaamaa G, Kaiser M, Hills E, Soim A, Zhu M, et al. Racial disparity in hypertensive disorders of pregnancy in New York State: a 10-year longitudinal population-based study. Am J Public Health. 2007;97(1):163-70. Epub 2006/12/02.

13. Savitz DA, Danilack VA, Engel SM, Elston B, Lipkind HS. Descriptive epidemiology of chronic hypertension, gestational hypertension, and preeclampsia in New York State, 1995-2004. Matern Child Health J. 2014;18(4):829-38. Epub 2013/06/25.

14. Silva LM, Coolman M, Steegers EA, Jaddoe VW, Moll HA, Hofman A, et al. Low socioeconomic status is a risk factor for preeclampsia: the Generation R Study. J Hypertens. 2008;26(6):1200-8. Epub 2008/05/14.

15. Kuklina EV, Ayala C, Callaghan WM. Hypertensive disorders and severe obstetric morbidity in the United States. Obstet Gynecol. 2009;113(6):1299-306. Epub 2009/05/23.

16. Roberts CL, Ford JB, Algert CS, Antonsen S, Chalmers J, Cnattingius S, et al. Population-based trends in pregnancy hypertension and pre-eclampsia: an international comparative study. BMJ Open. 2011;1(1):e000101. Epub 2011/10/25.

17. Berg CJ, Mackay AP, Qin C, Callaghan WM. Overview of maternal morbidity during hospitalization for labor and delivery in the United States: 1993-1997 and 2001-2005. Obstet Gynecol. 2009;113(5):1075-81. Epub 2009/04/23.

18. Bateman BT, Bansil P, Hernandez-Diaz S, Mhyre JM, Callaghan WM, Kuklina EV. Prevalence, trends, and outcomes of chronic hypertension: a nationwide sample of delivery admissions. Am J Obstet Gynecol. 2012;206(2):134 e1-8. Epub 2011/12/20.

19. Hamilton BE, Martin JA, Ventura SJ. Births: preliminary data for 2012. Natl Vital Stat Rep. 2013;62(3):1-20. Epub 2013/12/11.

20. LaCoursiere DY, Bloebaum L, Duncan JD, Varner MW. Population-based trends and correlates of maternal overweight and obesity, Utah 1991-2001. Am J Obstet Gynecol. 2005;192(3):832-9. Epub 2005/03/05.

21. Kim SY, Dietz PM, England L, Morrow B, Callaghan WM. Trends in pre-pregnancy obesity in nine states, 1993-2003. Obesity (Silver Spring). 2007;15(4):986-93. Epub 2007/04/12.

22. Bansil P, Kuklina EV, Meikle SF, Posner SF, Kourtis AP, Ellington SR, et al. Maternal and fetal outcomes among women with depression. J Womens Health (Larchmt). 2010;19(2):329-34. Epub 2010/01/26.

23. Geller SE, Rosenberg D, Cox SM, Brown ML, Simonson L, Driscoll CA, et al. The continuum of maternal morbidity and mortality: factors associated with severity. Am J Obstet Gynecol. 2004;191(3):939-44. Epub 2004/10/07.

24. Say L, Souza JP, Pattinson RC. Maternal near miss--towards a standard tool for monitoring quality of maternal health care. Best Pract Res Clin Obstet Gynaecol. 2009;23(3):287-96. Epub 2009/03/24.

25. Souza JP, Gulmezoglu AM, Vogel J, Carroli G, Lumbiganon P, Qureshi Z, et al. Moving beyond essential interventions for reduction of maternal mortality (the WHO Multicountry Survey on Maternal and Newborn Health): a cross-sectional study. Lancet. 2013;381(9879):1747-55. Epub 2013/05/21.

26. Chou D, Tuncalp O, Firoz T, Barreix M, Filippi V, von Dadelszen P, et al. Constructing maternal morbidity - towards a standard tool to measure and monitor maternal health beyond mortality. BMC Pregnancy Childbirth. 2016;16:45. Epub 2016/03/05.

27. Firoz T, Chou D, von Dadelszen P, Agrawal P, Vanderkruik R, Tuncalp O, et al. Measuring maternal health: focus on maternal morbidity. Bull World Health Organ. 2013;91(10):794-6. Epub 2013/10/12.

28. Severe Maternal Morbidity in the United States. Division of Reproductive Health, National Center for Chronic Disease Prevention and Health Promotion, Centers for Disease Control and Prevention. Accessed at: http://www.cdc.gov/reproductivehealth/maternalinfanthealth/severematernalmorbidity.html

29. Bacak SJ, Callaghan WM, Dietz PM, Crouse C. Pregnancy-associated hospitalizations in the United States, 1999-2000. Am J Obstet Gynecol. 2005;192(2):592-7. Epub 2005/02/08.

30. Bennett TA, Kotelchuck M, Cox CE, Tucker MJ, Nadeau DA. Pregnancy-associated hospitalizations in the United States in 1991 and 1992: a comprehensive view of maternal morbidity. Am J Obstet Gynecol. 1998;178(2):346-54. Epub 1998/03/21.

31. Danel I, Berg C, Johnson CH, Atrash H. Magnitude of maternal morbidity during labor and delivery: United States, 1993-1997. Am J Public Health. 2003;93(4):631-4. Epub 2003/03/28.

32. Geller SE, Rosenberg D, Cox S, Brown M, Simonson L, Kilpatrick S. A scoring system identified near-miss maternal morbidity during pregnancy. J Clin Epidemiol. 2004;57(7):716-20. Epub 2004/09/11.

33. Callaghan WM, Mackay AP, Berg CJ. Identification of severe maternal morbidity during delivery hospitalizations, United States, 1991-2003. Am J Obstet Gynecol. 2008;199(2):133 e1-8. Epub 2008/02/19.

34. Callaghan WM, Creanga AA, Kuklina EV. Severe maternal morbidity among delivery and postpartum hospitalizations in the United States. Obstet Gynecol. 2012;120(5):1029-36. Epub 2012/10/24.

35. Kuklina EV, Meikle SF, Jamieson DJ, Whiteman MK, Barfield WD, Hillis SD, et al. Severe obstetric morbidity in the United States: 1998-2005. Obstet Gynecol. 2009;113(2 Pt 1):293-9. Epub 2009/01/22.

36. Main EK, Abreo A, McNulty J, Gilbert W, McNally C, Poeltler D, et al. Measuring severe maternal morbidity: validation of potential measures. Am J Obstet Gynecol. 2016;214(5):643 e1- e10. Epub 2015/11/20.

37. Sigakis MJ, Leffert LR, Mirzakhani H, Sharawi N, Rajala B, Callaghan WM, et al. The Validity of Discharge Billing Codes Reflecting Severe Maternal Morbidity. Anesth Analg. 2016;123(3):731-8. Epub 2016/07/09.

38. Severe Maternal Morbidity in the United States. Center for Disease Control and Prevention; [updated September 22, 2015; cited 2016 March 18]; Available from: http://www.cdc.gov/reproductivehealth/maternalinfanthealth/severematernalmorbidity.html.

39. Kilpatrick SJ, Abreo A, Gould J, Greene N, Main EK. Confirmed severe maternal morbidity is associated with high rate of preterm delivery. Am J Obstet Gynecol. 2016;215(2):233 e1-7. Epub 2016/02/24.

40. Grobman WA, Bailit JL, Rice MM, Wapner RJ, Reddy UM, Varner MW, et al. Frequency of and factors associated with severe maternal morbidity. Obstet Gynecol. 2014;123(4):804-10. Epub 2014/05/03.

41. Lyndon A, Lee HC, Gilbert WM, Gould JB, Lee KA. Maternal morbidity during childbirth hospitalization in California. J Matern Fetal Neonatal Med. 2012;25(12):2529-35. Epub 2012/07/12.

42. Gray KE, Wallace ER, Nelson KR, Reed SD, Schiff MA. Population-based study of risk factors for severe maternal morbidity. Paediatr Perinat Epidemiol. 2012;26(6):506-14. Epub 2012/10/16.

43. Creanga AA, Bateman BT, Kuklina EV, Callaghan WM. Racial and ethnic disparities in severe maternal morbidity: a multistate analysis, 2008-2010. Am J Obstet Gynecol. 2014;210(5):435 e1-8. Epub 2013/12/04.

44. Witteveen T, Van Den Akker T, Zwart JJ, Bloemenkamp KW, Van Roosmalen J. Severe acute maternal morbidity in multiple pregnancies: a nationwide cohort study. Am J Obstet Gynecol. 2016;214(5):641 e1- e10. Epub 2015/11/19.

45. Belanoff C, Declercq ER, Diop H, Gopal D, Kotelchuck M, Luke B, et al. Severe Maternal Morbidity and the Use of Assisted Reproductive Technology in Massachusetts. Obstet Gynecol. 2016;127(3):527-34. Epub 2016/02/09.

46. Martin AS, Monsour M, Kissin DM, Jamieson DJ, Callaghan WM, Boulet SL. Trends in Severe Maternal Morbidity After Assisted Reproductive Technology in the United States, 2008-2012. Obstet Gynecol. 2016;127(1):59-66. Epub 2015/12/10.

47. Zhang J, Meikle S, Trumble A. Severe maternal morbidity associated with hypertensive disorders in pregnancy in the United States. Hypertens Pregnancy. 2003;22(2):203-12. Epub 2003/08/12.

48. Campbell KH, Savitz D, Werner EF, Pettker CM, Goffman D, Chazotte C, et al. Maternal morbidity and risk of death at delivery hospitalization. Obstet Gynecol. 2013;122(3):627-33. Epub 2013/08/08.

49. Wanderer JP, Leffert LR, Mhyre JM, Kuklina EV, Callaghan WM, Bateman BT. Epidemiology of obstetric-related ICU admissions in Maryland: 1999-2008*. Crit Care Med. 2013;41(8):1844-52. Epub 2013/05/08.

50. Kozhimannil KB, Arcaya MC, Subramanian SV. Maternal clinical diagnoses and hospital variation in the risk of cesarean delivery: analyses of a National US Hospital Discharge Database. PLoS Med. 2014;11(10):e1001745. Epub 2014/10/22.

51. van Dillen J, Zwart J, Schutte J, van Roosmalen J. Maternal sepsis: epidemiology, etiology and outcome. Curr Opin Infect Dis. 2010;23(3):249-54. Epub 2010/04/09.

52. Roberts JM, Pearson G, Cutler J, Lindheimer M. Summary of the NHLBI Working Group on Research on Hypertension During Pregnancy. Hypertension. 2003;41(3):437-45. Epub 2003/03/08.

53. Conde-Agudelo A, Romero R. Amniotic fluid embolism: an evidence-based review. Am J Obstet Gynecol. 2009;201(5):445 e1-13. Epub 2009/11/03.

54. Tata LJ, Lewis SA, McKeever TM, Smith CJ, Doyle P, Smeeth L, et al. A comprehensive analysis of adverse obstetric and pediatric complications in women with asthma. Am J Respir Crit Care Med. 2007;175(10):991-7. Epub 2007/02/03.

55. Persson M, Norman M, Hanson U. Obstetric and perinatal outcomes in type 1 diabetic pregnancies: A large, population-based study. Diabetes Care. 2009;32(11):2005-9. Epub 2009/08/14.

56. Grigoriadis S, VonderPorten EH, Mamisashvili L, Tomlinson G, Dennis CL, Koren G, et al. The impact of maternal depression during pregnancy on perinatal outcomes: a systematic review and meta-analysis. J Clin Psychiatry. 2013;74(4):e321-41. Epub 2013/05/10.

57. Burns L, Mattick RP, Cooke M. The use of record linkage to examine illicit drug use in pregnancy. Addiction. 2006;101(6):873-82. Epub 2006/05/16.

58. Committee Opinion No. 666 Summary: Optimizing Postpartum Care. Obstet Gynecol. 2016;127(6):1192-3. Epub 2016/05/24.

59. Belfort MA, Clark SL, Saade GR, Kleja K, Dildy GA, 3rd, Van Veen TR, et al. Hospital readmission after delivery: evidence for an increased incidence of nonurogenital infection in the immediate postpartum period. Am J Obstet Gynecol. 2010;202(1):35 e1-7. Epub 2009/11/06.

60. Kestenbaum B, Seliger SL, Easterling TR, Gillen DL, Critchlow CW, Stehman-Breen CO, et al. Cardiovascular and thromboembolic events following hypertensive pregnancy. Am J Kidney Dis. 2003;42(5):982-9. Epub 2003/10/29.

61. Savitz DA, Danilack VA, Elston B, Lipkind HS. Pregnancy-induced hypertension and diabetes and the risk of cardiovascular disease, stroke, and diabetes hospitalization in the year following delivery. Am J Epidemiol. 2014;180(1):41-4. Epub 2014/06/01.

62. Declercq E, Barger M, Cabral HJ, Evans SR, Kotelchuck M, Simon C, et al. Maternal outcomes associated with planned primary cesarean births compared with planned vaginal births. Obstet Gynecol. 2007;109(3):669-77. Epub 2007/03/03.

63. Grullon KE, Grimes DA. The safety of early postpartum discharge: a review and critique. Obstet Gynecol. 1997;90(5):860-5. Epub 1997/11/14.

64. Liu S, Heaman M, Kramer MS, Demissie K, Wen SW, Marcoux S. Length of hospital stay, obstetric conditions at childbirth, and maternal readmission: a population-based cohort study. Am J Obstet Gynecol. 2002;187(3):681-7. Epub 2002/09/19.

65. Sharvit M, Rubinstein T, Ravid D, Shechter-Maor G, Fishman A, Biron-Shental T. Patients with high-risk pregnancies and complicated deliveries have an increased risk of maternal postpartum readmissions. Arch Gynecol Obstet. 2014;290(4):629-33. Epub 2014/05/08.

66. Bernstein HH, Spino C, Lalama CM, Finch SA, Wasserman RC, McCormick MC. Unreadiness for postpartum discharge following healthy term pregnancy: impact on health care use and outcomes. Acad Pediatr. 2013;13(1):27-39. Epub 2012/10/27.

67. Clark SL, Belfort MA, Dildy GA, Englebright J, Meints L, Meyers JA, et al. Emergency department use during the postpartum period: implications for current management of the puerperium. Am J Obstet Gynecol. 2010;203(1):38 e1-6. Epub 2010/04/27.

68. Haas JS, McCormick MC. Hospital use and health status of women during the 5 years following the birth of a premature, low-birthweight infant. Am J Public Health. 1997;87(7):1151-5. Epub 1997/07/01.

69. Donahue D, Brooten D, Roncoli M, Arnold L, Knapp H, Borucki L, et al. Acute care visits and rehospitalization in women and infants after cesarean birth. J Perinatol. 1994;14(1):36-40. Epub 1994/01/01.

70. Pollock W, Rose L, Dennis CL. Pregnant and postpartum admissions to the intensive care unit: a systematic review. Intensive Care Med. 2010;36(9):1465-74. Epub 2010/07/16.

71. McDonald SD, Malinowski A, Zhou Q, Yusuf S, Devereaux PJ. Cardiovascular sequelae of preeclampsia/eclampsia: a systematic review and meta-analyses. Am Heart J. 2008;156(5):918-30. Epub 2008/12/09.

72. Bellamy L, Casas JP, Hingorani AD, Williams DJ. Pre-eclampsia and risk of cardiovascular disease and cancer in later life: systematic review and meta-analysis. BMJ. 2007;335(7627):974. Epub 2007/11/03.

73. Magnussen EB, Vatten LJ, Smith GD, Romundstad PR. Hypertensive disorders in pregnancy and subsequently measured cardiovascular risk factors. Obstet Gynecol. 2009;114(5):961-70. Epub 2010/02/20.

74. Mosca L, Benjamin EJ, Berra K, Bezanson JL, Dolor RJ, Lloyd-Jones DM, et al. Effectiveness-based guidelines for the prevention of cardiovascular disease in women--2011 update: a guideline from the american heart association. Circulation. 2011;123(11):1243-62. Epub 2011/02/18.

75. Hamilton MS, Brooten D, Youngblut JM. High-risk pregnancy: postpartum rehospitalization. J Perinatol. 2002;22(7):566-71. Epub 2002/10/09.

76. Bennett WL, Chang HY, Levine DM, Wang L, Neale D, Werner EF, et al. Utilization of primary and obstetric care after medically complicated pregnancies: an analysis of medical claims data. J Gen Intern Med. 2014;29(4):636-45. Epub 2014/01/30.

77. Black MH, Zhou H, Sacks DA, Dublin S, Lawrence JM, Harrison TN, et al. Hypertensive disorders first identified in pregnancy increase risk for incident prehypertension and hypertension in the year after delivery. J Hypertens. 2016;34(4):728-35. Epub 2016/01/26.

78. Brown DW, Dueker N, Jamieson DJ, Cole JW, Wozniak MA, Stern BJ, et al. Preeclampsia and the risk of ischemic stroke among young women: results from the Stroke Prevention in Young Women Study. Stroke. 2006;37(4):1055-9. Epub 2006/02/18.

79. Lain SJ, Hadfield RM, Raynes-Greenow CH, Ford JB, Mealing NM, Algert CS, et al. Quality of data in perinatal population health databases: a systematic review. Med Care. 2012;50(4):e7-20. Epub 2011/05/28.

80. Lydon-Rochelle MT, Holt VL, Cardenas V, Nelson JC, Easterling TR, Gardella C, et al. The reporting of pre-existing maternal medical conditions and complications of pregnancy on birth certificates and in hospital discharge data. Am J Obstet Gynecol. 2005;193(1):125-34. Epub 2005/07/16.

81. Callaghan WM, Grobman WA, Kilpatrick SJ, Main EK, D'Alton M. Facility-based identification of women with severe maternal morbidity: it is time to start. Obstet Gynecol. 2014;123(5):978-81. Epub 2014/05/03.

82. Berg C DI, Atrash H, Zane S, Bartlett L (Editors). Strategies to reduced pregnancy-related deaths: from identification and review to action. Atlanta: Center for Disease Control and Prevention, 2001.

83. Romundstad PR, Magnussen EB, Smith GD, Vatten LJ. Hypertension in pregnancy and later cardiovascular risk: common antecedents? Circulation. 2010;122(6):579-84. Epub 2010/07/28.

84. Ben-Shlomo Y, Kuh D. A life course approach to chronic disease epidemiology: conceptual models, empirical challenges and interdisciplinary perspectives. Int J Epidemiol. 2002;31(2):285-93. Epub 2002/05/01.

85. Misra DP, Guyer B, Allston A. Integrated perinatal health framework. A multiple determinants model with a life span approach. Am J Prev Med. 2003;25(1):65-75. Epub 2003/06/24.

86. Ehrenthal DB, Catov JM. Importance of engaging obstetrician/gynecologists in cardiovascular disease prevention. Curr Opin Cardiol. 2013;28(5):547-53. Epub 2013/08/10.

87. Berends AL, de Groot CJ, Sijbrands EJ, Sie MP, Benneheij SH, Pal R, et al. Shared constitutional risks for maternal vascular-related pregnancy complications and future cardiovascular disease. Hypertension. 2008;51(4):1034-41. Epub 2008/02/09.

88. Freibert SM, Mannino DM, Bush H, Crofford LJ. The association of adverse pregnancy events and cardiovascular disease in women 50 years of age and older. J Womens Health (Larchmt). 2011;20(2):287-93. Epub 2011/01/27.

Chapter Three: Research Design and Methods

Overview

This chapter describes the study methods to evaluate the relation between maternal hypertensive disorders and severe maternal morbidity at delivery and the impact of each on maternal morbidity in the first year postpartum. This chapter begins with the study aims and hypotheses, followed by the study design and data sources. Descriptions are then presented for the dependent and independent variables. The final section presents the analytic plan for each of the study aims, including statistical models.

Study Aims and Hypotheses

Based on the population of deliveries to women residing in Massachusetts using maternal hospital delivery discharge records from January 1, 2000-December 31, 2012 linked with birth certificate and fetal death record data, the following aims and hypotheses were evaluated:

Aim 1

Evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with severe maternal morbidity at delivery.

1) $H_{0(null)}$: There is no association between maternal hypertensive disorders in pregnancy and severe maternal morbidity at delivery.

2) $H_{0(null)}$: There is no association between chronic and pregnancy-associated conditions in pregnancy and severe maternal morbidity at delivery.

Aim 2

Evaluate the relation between severe maternal morbidity at delivery and postpartum maternal rehospitalization in the year following delivery among women without chronic medical diseases.

*1) $H_{0(null)}$: There is no association between severe maternal morbidity at delivery and rehospitalization in the yea*r *following delivery among women without chronic medical conditions.*

Aim 3

Evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with postpartum maternal rehospitalization in the year following delivery independent of severe maternal morbidity at delivery.

1) $H_{0(null)}$: There is no association between maternal hypertensive disorders in pregnancy and rehospitalization in the year following delivery, independent of severe maternal morbidity at delivery

2) $H_{0(null)}$:: There is no association between chronic and pregnancy-associated conditions and rehospitalization in the year following delivery, independent of severe maternal morbidity at delivery

3) $H_{0(null)}$: The relation of maternal hypertensive disorders and other chronic and pregnancy-associated conditions does not differ for deliveries to women with and without severe maternal morbidity at delivery

Null hypotheses were included due to lack of prior studies to indicate which hypertensive disorders or other chronic or pregnancy-associated conditions may be related to severe maternal morbidity and the relation between severe maternal morbidity and subsequent rehospitalization outcomes.

Study Design

In Aim 1, the study design was a retrospective cohort design based on deliveries among resident women in Massachusetts from 2000-2012; the exposure of maternal hypertensive disorders and other chronic and pregnancy-associated conditions before and during pregnancy were documented on vital records and hospital delivery discharge records and severe maternal morbidity (SMM) at delivery was assessed based on hospital delivery discharge records. For Aim 2, the study was a retrospective cohort study of deliveries among resident women in Massachusetts without chronic medical conditions from 2002-2011, with the exposure of SMM collected at the time of delivery on hospital delivery discharge records and the outcome collected within the first year postpartum using non-delivery hospital discharge, observational stay, and emergency department records. For Aim 3, a retrospective cohort design examined all deliveries among resident women in Massachusetts from 2002-2011, with the exposure of hypertensive disorders and other chronic and pregnancy-associated conditions before and during pregnancy documented on vital records and hospital delivery discharge records and the outcome collected for the first year postpartum on hospital discharge, observational stay, and emergency department records. Across all aims, multiple deliveries to the same woman were included and analytic methods were used to adjust for these multiple deliveries over the study period.

Data Sources

Data were obtained from the Pregnancy to Early Life Longitudinal (PELL) data system, a population-based data system housed at the Massachusetts Department of Public Health (MDPH). The PELL data system is a longitudinally linked database of Massachusetts mothers and their children, which includes vital statistics records, hospital discharge records, and public health program participation data.

Vital statistics and hospital utilization data were used for this study. Birth certificate data and hospital discharge data are mandated by law to be reported to the Massachusetts Department of Public Health (M.G.L. c.111§24B and M.G.L. c.12C§8). Birth certificate data includes information on the place of birth, date, name, race/ethnicity and sex of child, as well as demographic information about the mother and father and the mother's birth history. The birth certificate also includes information about maternal risk factors of pregnancy as well as labor and delivery complications. Birth certificates are filed by city or town clerks and forwarded electronically to the state Department of Public Health. In 2011, the Massachusetts Department of Pubic Heath initiated the Vitals Information Partnership, an electronic birth registration interactive module, and updated the birth certificate to the 2003 US Standard Certificate of Live Birth. Massachusetts requires fetal death reporting if a fetus is of at least twenty weeks gestation or at least 350g (M.G.L. c.111§202). Massachusetts law also requires death certificates to report information including: date of death, age of decedent and disease or cause of death (M.G.L. c.46§1).

Hospital discharge data include the maternal hospital discharge for the delivery hospitalization as well as non-delivery hospitalizations, observational stays, and

emergency department visit records. These data systems contain some limited demographic information about the patient as well as principal diagnoses related to the admission, procedures completed, length of stay, costs, and sources of payment. Both diagnoses and procedures are coded using the International Classification of Disease Manual, 9th revision, Clinical Modification edition. There are up to fifteen potential diagnosis and procedure coding fields for hospital discharge, and six each for observational stay and emergency department records. As an administrative database, hospital discharge records are generally filed to procure payment; coding may more accurately reflect medical-surgical conditions that affect reimbursement rather than obstetric diagnoses (1). Hospital discharge data also provide a population-based means to conduct public health surveillance. Importantly, births that happen outside of a hospital setting are captured through the birth certificate but not through hospital discharge records.

Both deterministic and probabilistic methods are used to link records from the various datasets to the PELL data system using LinkPro software (InfoSoft, Inc.; Winnipeg, Manitoba, Canada). Selected linkage variables include facility code, medical record number, date of birth/date of delivery, sex, zip code, and birth weight. Previous studies using the PELL data system have reported the linkage rate of deliveries to maternal hospital discharge records to be 99.2% (2). For Aim 1, PELL data were obtained for maternal hospital delivery discharge data from January 1, 2000-December 31, 2012 and linked to birth certificate data, fetal death certificate data, with a linkage of 99.0%.

For Aims 2 and 3, the matched data from Aim 1 were used for 2002-2011 and linked to prospective maternal non-delivery hospital discharges, observational stays, emergency department admissions and death data from 2002-2012 through a unique maternal identifier to capture rehospitalization in the first year postpartum. Emergency department data first became available for analysis in 2002 and the most recently linked data available from PELL are for 2012.

Massachusetts adopted the 2003 U.S. Standard Certificate of Live Birth starting in 2011. New variables of note on the 2003 revision included maternal height and pre-pregnancy weight to determine body mass index and a new categorization of maternal smoking before and during pregnancy. For all analyses, birth certificate data were coded to match 2000-2010 variable data with 2011-2012 variables.

Data access was authorized by the Massachusetts Department of Public Health in accordance with M.G.L c.111 §24A and the Massachusetts Center for Health Information and Analysis. The Institutional Review Board at Johns Hopkins Bloomberg School of Public Health determined this study to be exempt under 45 CFR 46.101(b), Category (4) due to the use of existing de-identified data in a limited use dataset.

Study Population

For Aim 1, the study population included deliveries to Massachusetts resident women with a Massachusetts occurent hospital delivery discharge record for either a live birth or fetal death from January 1, 2000-December 31, 2012. There were 988,285 deliveries of births and 5,047 deliveries of fetal deaths from 2000-2012, of which 970,353 were unique maternal deliveries that included 22,968 deliveries with plurality

greater than one (21,532 twin, 700 triplets, and 26 quadruplet or greater records). There were 986,745 hospital delivery discharge records from the same period. Data were merged by unique maternal identifier, providing 960,982 matched birth/fetal death and hospital delivery discharge records; 9,371 birth/fetal death records did not merge, of which a majority were births at home, birthing centers, or military centers, and did not have a hospital delivery discharge record. There also were 25,763 hospital delivery discharge records that did not merge, likely explained by the fact that the birth certificate/fetal death certificate files do not capture non-residents births or births to MA residents out of state. The matched 960,982 records represent deliveries to 643,874 unique women; 60.8% (n=390,684) had one delivery 30.8% (n=197,762) had two deliveries, and 8.4% (55,425) had three or more deliveries during the study period.

For Aims 2 and 3, the study population was drawn from deliveries to women from January 1, 2002-December 31, 2011 to allow for one year of postpartum follow-up through the end of 2012 as well as uniform linkage with hospital utilization data; emergency department records data became available statewide in 2002. For Aim 2, it was narrowed to deliveries to women without chronic medical conditions; 735,576 deliveries to women in Massachusetts from 2002-2011 were initially identified from hospital delivery discharge records linked to birth certificate and fetal death records that informed Aim 1. Women with pre-existing chronic conditions of asthma, autoimmune conditions, pre-existing diabetes, chronic hypertension and superimposed preeclampsia were excluded to examine the relation between events at delivery and morbidity postpartum. These conditions were identified from the birth certificate and fetal death records and the hospital delivery discharge records based on the results of Aim 1. A total

of 50,348 linked birth certificate, fetal death, and hospital delivery discharge records were excluded from analysis for these conditions. The final study sample for Aim 2 was 685,228 deliveries to women.

For Aim 3, all deliveries to Massachusetts resident women with a Massachusetts occurent hospital delivery discharge record for either a live birth or fetal death from January 1, 2002-December 31, 2011 were included. There were 735,576 such deliveries in Massachusetts from 2002-2011 identified from hospital delivery discharge records linked to birth certificate and fetal death records. Non-delivery hospital discharge, observational stay, and emergency department admission records from 2002 through the end of 2012 were linked with these data through a unique maternal identifier to capture one year postpartum follow-up.

Dependent Variables

Aim 1

The main dependent variable for Aim 1 was severe maternal morbidity (SMM) at delivery, defined by the methods of Callaghan et al. (2008) and Kuklina et al. (2009), and updated by Callaghan et al. (2012) (3-6). SMM is based on the presence or absence of twenty-five conditions a woman may experience at delivery (**Table 3.1**). Although a woman may have multiple indicators of SMM, this variable was dichotomous, consistent with previous research. Twenty-five ICD-9-CM diagnosis and procedure codes from any of the fifteen diagnosis and fifteen procedure code fields in the hospital delivery discharge record were first used to identify SMM; these criteria have reasonably high sensitivity (0.77) and a positive predictive value of 0.44 (6). SMM-indicated deliveries with short lengths of stay, defined as $\leq 90^{th}$ percentile for method of delivery (calculated

separately for vaginal, primary cesarean, repeat cesarean), were reclassified as hospitalization without SMM. Based on previous methods, the severity recalculation was not applied to transfers, deaths, or procedure-based codes, such as ventilation or hysterectomy. **Table 3.1** shows the 25 diagnosis and procedure categories that are included in the overall measure of SMM. Eclampsia, although a category of hypertensive disorders during pregnancy as recognized by ACOG, was considered an outcome of SMM at birth in this analysis as defined by Callaghan et al. (2008) (4).

The ICD-9-CM code for one indicator of SMM, blood transfusion, does not include information about the number of units transfused and may inflate the rate of SMM for women with only that indication; sensitivity analyses were conducted for SMM with and without blood transfusion (7). Further, a dichotomous variable defined by at least one cardiac-related SMM indicator was identified based on hypothesized relations with hypertension, as noted in previous research. It was examined as another outcome in Aim 1, both with and without the shock indication (See **Table 3.1** for the cardiac-related SMM indicators) (8).

Table 3.1 Severe Maternal Morbidity Indications and Corresponding ICD-9-CM Coding

Severe Maternal Morbidity Indicator	ICD-9-CM Codes	Cardiac-related indicator
1. Acute myocardial infarction	410.xx	x
2. Acute renal failure	584.x, 669.3x	
3. Adult respiratory distress syndrome	518.5, 518.81, 518.82, 518.84,799.1	
4. Amniotic fluid embolism	673.1x	
5. Aneurysm	441.xx	
6. Cardiac arrest/ventricular fibrillation	427.41, 427.42, 427.5	x
7. Disseminated intravascular coagulation	286.6, 286.9, 666.3x	
8. Eclampsia	642.6x	
9. Heart failure during procedure or surgery	669.4x, 997.1	x
10. Internal injuries of thorax, abdomen, and	860.xx—869.xx	

pelvis		
11. Intracranial injuries	800.xx, 801.xx, 803.xx, 804.xx, 851.xx-854.xx	
12. Puerperal cerebrovascular disorders	430, 431, 432.x, 433.xx, 434.xx, 436, 437.x, 671.5x, 674.0x, 997.2, 999.2	
13. Pulmonary edema	428.1, 518.4	
14. Severe anesthesia complications	668.0x, 668.1x, 668.2x	
15. Sepsis	038.xx, 995.91, 995.92	
16. Shock	669.1x, 785.5x, 995.0, 995.4, 998.0	x[1]
17. Sickle cell anemia with crisis	282.62, 282.64, 282.69	
18. Thrombotic embolism	415.1x, 673.0x, 673.2x, 673.3x, 673.8x	
19. Blood transfusion	99.0x	
20. Cardio monitoring	89.6x	x
21. Conversion of cardiac rhythm	99.6x	x
22. Hysterectomy	68.3x-68.9	
23. Operations on heart and pericardium	35.xx, 36.xx, 37.xx, 39.xx	x
24. Temporary tracheostomy	31.1	
25. Ventilation	93.90, 96.01-96.05, 96.7x	

[1]The cardiac-related SMM indicator was considered both with and without shock

Aims 2 and 3

For Aims 2 and 3, the dependent variable was at least one non-injury, non-antenatal-related hospital encounter within the first year after delivery; it was considered separately by type: hospital discharge, observational stay, or emergency department visit. Analyses also examined hospital encounters within six weeks postpartum, to align with the standard definitions of pregnancy-related mortality in the United States (9, 10).

For each type of hospital encounter, all diagnosis code fields in the record were first scanned for injury-related ICD-9-CM codes, using methods from previous studies **(Table 3.2**) (11). The number of diagnosis code fields varied by type of hospital encounter: non-delivery hospital discharge records had fifteen fields and observational stay and emergency department records each had six fields. Diagnosis code fields were also scanned for antenatal-related conditions based on previously published methods (**Table 3.2**) (12). Hospitals encounters indicated for injury-related or antenatal- diagnosis

codes were excluded from analyses. The death file from 2002-2012 was also linked to identify maternal deaths within the first year postpartum (N=160). Maternal deaths were described by timing and hospital encounter. Based on preliminary analysis and low numbers, women who died within the first year after delivery remained in the analysis; sensitivity analyses were conducted with and without maternal deaths.

Table 3.2 Injury- and Antenatal-related ICD-9-CM Coding

Group	ICD-9-CM Coding
Injury-related	800-999.99 with excluded codes for late effects of injuries, adverse drug effects and medical care-related injuries: E849, E870-E876, E878-879, E929, E930-E949, E959, E969, E977, E989, E999
Antenatal-related	Fifth digit of 3 in ICD-9-CM codes for primary or secondary diagnosis 630-677, V22, V23, V28, or 792.3

Independent Variables

This section first discusses the main independent variables by study aim, followed by other social and biological independent covariates, which were also examined across all aims.

Aim 1

The main independent variable in Aim 1 was maternal hypertensive disorders in pregnancy. In addition, other prevalent maternal chronic and pregnancy-associated conditions of asthma, autoimmune conditions, depression, gestational diabetes, pre-existing diabetes, and substance use disorders were examined as key variables, as well as their relation to hypertensive disorders.

Hypertensive disorders in pregnancy

To expand approaches used in previous research, this study examined subcategories of hypertensive disorders: chronic hypertension, gestational hypertension, mild and severe preeclampsia, and super-imposed preeclampsia. Both birth certificate and maternal hospital discharge at delivery data were used to ascertain chronic hypertension and gestational hypertension (**Table 3.3**) (13, 14). In the maternal hospital delivery discharge data, the 15 diagnosis codes fields were scanned to identify maternal hypertensive disorders using the International Classification of Disease, 9th revision, Clinical Modification (ICD-9-CM). The ability to use multiple databases, including hospital administrative databases and vital statistics, presented an opportunity to improve ascertainment of these variables. Previous research indicates that combining hospital discharge record and birth certificate data improves ascertainment of hypertension than either record alone (15, 16). One recent US study validated the medical record against the hospital discharge record, birth certificate data, and the data combined for classifying hypertensive disorders (15). Findings showed underestimation of chronic hypertension and gestational hypertension by the birth certificate or hospital discharge data alone; combining the two data sources provided more complete identification of chronic and gestational hypertension than the birth certificate data alone, as assessed by true positive fractions (15).

Classification of hypertensive disorders during pregnancy was hierarchical and mutually exclusive, identifying in order: superimposed preeclampsia, severe preeclampsia, mild preeclampsia, chronic hypertension, gestational hypertension, and no hypertension. If there were conflicting reports on the vital records and hospital discharge

data, the more severe code was used. In the hospital discharge record diagnosis coding fields, the International Classification of Disease, 9th revision, Clinical Modification (ICD-9-CM) manual lists outdated terms of essential and transient hypertension; therefore, as in previous studies, essential and pre-existing hypertension codes identified chronic hypertension and gestational hypertension included the transient hypertension codes (**Table 3.3**) (17, 18). Unspecified hypertension, a condition listed in the ICD-9-CM manual, was not used to inform hypertensive categories as previous research varies on its interpretation (17, 19).

For chronic hypertension, 41.4% (n=6,246) of cases were identified by both sources, 31.8% (n=4,791) were identified only on the hospital delivery discharge record, and 26.8% (n=4,040) were identified only on the birth certificate/fetal death record. For gestational hypertension, 39.8% (n=14,199) of cases were identified by both sources, 41.0% (n=14,634) only on the hospital delivery discharge record, and 19.2% (n=6,863) only on the birth certificate/fetal death record. In cases of multiple gestations, any indication of gestational or chronic hypertension on any one birth certificate or fetal death record indicated presence of the condition for that delivery.

Asthma, Autoimmune conditions, Depression, Gestational diabetes, Pre-existing diabetes, Substance use disorders

Based on previous research, other common chronic and pregnancy-associated conditions among pregnant women include diabetes (pre-existing and gestational), asthma, substance use disorders, depression and autoimmune conditions (20). ICD-9-CM codes, informed from previous studies and national definitions, were scanned in each diagnostic field of the maternal delivery discharge record for these chronic conditions

(21, 22) (See **Table 3.3**). With the exception of pre-existing and gestational diabetes, as noted below, any classification of chronic conditions in any of the 15 diagnosis codes on the maternal hospital delivery discharge record indicated the presence of a chronic condition. If an ICD-9-CM code was not listed in any field, these conditions were coded as not present to create dichotomous variables, indicating the presence or absence of the condition. The sensitivities for coding chronic conditions on the hospital discharge data are found to be low; in a recent systematic review, Lain et al. (2012) found the sensitivity for asthma to range between 12.3-42.0% (16). The specificity of asthma, however, was high ranging from 98.9-99.4. Caution is made in interpreting the coefficients of these variables with low sensitivity in the analyses.

Birth certificate data supplemented ICD-9-CM diagnosis codes on the maternal hospital delivery discharge record for exposure ascertainment for pre-existing and gestational diabetes (14). A mutually exclusive hierarchical categorization was implemented; if data sources conflicted, pre-existing diabetes took precedence. For pre-existing diabetes, 24.0% (n=3,888) of cases were identified by both sources, 21.8% (n=2,384) were identified only on the hospital delivery discharge record, and 42.7% (n=4,677) only on the birth certificate/fetal death record. For gestational diabetes, 61.1% (n=30,098) of cases were identified by both sources, 26.5% (n=13,039) only on the hospital delivery discharge record, and 12.4% (n=6,123) only on the birth certificate/fetal death record. Similar to the hypertensive variables, when records were aggregated by delivery in the case of multiple gestations, any indication of pre-existing or gestational diabetes on any birth certificate or fetal death record indicated presence of the condition.

Table 3.3 Preexisting and Pregnancy-associated Conditions, Data Sources and Coding

Aim	Variable	Source	Numeric/Categorical Response Categories
1,2,3	Superimposed preeclampsia	HDD	1: ICD-9-CM codes: 642.7x; Otherwise, scan for other hypertensive codes
1,2,3	Severe preeclampsia	HDD	2: ICD-9-CM codes: 642.5x; Otherwise, scan for other hypertensive codes
1,2,3	Mild preeclampsia	HDD	3: ICD-9-CM codes: 642.4x; Otherwise, scan for other hypertensive codes
1,2,3	Chronic hypertension	BC, FD, HDD	4: BC or ICD-9-CM codes: 642.0x, 642.1x, 642.2x, 401.x, 405.x, 416.0x 459.3x; Otherwise, scan for other hypertensive codes
1,2,3	Gestational hypertension	BC, FD, HDD	5: BC or ICD-9-CM codes: 642.3x; 0: Otherwise, none (reference)
1,2,3	Pre-existing diabetes	BC, FD, HDD	1: BC or ICD-9-CM codes: 250, 249, 362.01-362.06, 366.41, 357.2, 648.0; Otherwise, Scan for gestational diabetes
1,2,3	Gestational diabetes	BC, FD, HDD	2: BC or ICD-9-CM codes: 648.8; 0: Otherwise, none (reference)
1,2,3	Asthma (CMS)	HDD	1: ICD-9-CM codes: 493; 0: Otherwise, No (reference)
1,2,3	Autoimmune conditions (21)	HDD	1: ICD-9-CM codes: 130.3, 136.1, 242.0, 283.0, 340, 357.0, 358.0, 358.1, 379.4, 390-398, 422, 429.0, 446.0-446.2, 446.4, 446.7, 516.3, 517.0, 547.2, 555, 556, 579.0, 580, 581.3, 581.9, 582, 583.0-583.4, 694.0, 694.2-694.6, 696.0, 696.1, 701.0, 710.1, 710.0, 710.3, 710.4, 714.0-714.3, 720.0, 851.1; 0: Otherwise, No (reference)
1,2,3	Depression (CMS OASH)	HDD	1: ICD-9-CM codes: 296.2, 296.3, 296.5, 296.6, 296.89, 298, 300.4, 309.1, 311; 0: Otherwise, No (reference)
1,2,3	Substance use disorders (23)	HDD	1: ICD-9-CM codes: 291, 292, 303, 304, 305.0, 305.2-305.7, 305.9; 0: Otherwise, No (reference)

Aim 2

Severe Maternal Morbidity at Delivery

The main independent variable in Aim 2 was SMM at delivery, as described above as the dependent variable in Aim 1. SMM was considered both with and without the blood transfusion indicator in all analyses. In addition, the number of SMM indicators

was examined as a sensitivity analysis on a scale of 0, 1, or 2+ indicators to further understand the relation between SMM at delivery hospitalization and postpartum hospital encounters.

Aim 3

Maternal Hypertensive Disorders and other Chronic and Pregnancy-associated Conditions at Delivery

In Aim 3, the main independent variable was maternal hypertensive disorders in pregnancy. In addition, other prevalent maternal chronic and pregnancy-associated conditions of asthma, autoimmune conditions, depression, gestational diabetes, pre-existing diabetes, and substance use disorders were also examined as key variables, particularly in their relation to hypertensive disorders. These variables were described in more detail in Aim 1.

Severe Maternal Morbidity at Delivery

Another key variable in Aim 3 was SMM at delivery, as described above as the main dependent variable in Aim 1 and the main independent variable in Aim 2. Similar to Aim 2, SMM was considered both with and without the blood transfusion indicator in all analyses. In addition, the number of SMM indicators was examined as a sensitivity analysis on a scale of 0, 1, or 2+ indicators to further understand the relation between SMM at delivery hospitalization and postpartum hospital encounters.

Other Covariates

Main covariates, including social and biological variables, were informed by the conceptual model available on either vital records or hospital discharge data: mother's age, race/ethnicity, maternal education, insurance delivery payer, calendar time, hospital

level, prenatal care initiation, parity, plurality, current low birth weight delivery, smoking, method of delivery, marital status, and congenital cardiac disease (**Table 3.4**). These covariates were ascertained from the birth certificate and, if available, also from the hospital discharge delivery record. For Aims 2 and 3, an additional covariate of length of stay of delivery hospitalization was included. Description of covariates was based on data for Aim 1 for deliveries from 2000-2012, which was inclusive of the data for Aims 2 and 3.

Year of delivery was based on the birth certificate and fetal death records to represent the calendar year of delivery. The largest number of births occurred in 2000 and the least in 2012, with an overall decrease by 11.1% over the time period, reflecting overall declines in birth rates.

Hospital level was based on the facility of birth information on the birth certificate and fetal death records. MDPH staff in the Office of Data Translation in the Bureau of Family Health and Nutrition have aligned facilities with hospital designations from 2000-2012. Level I facilities are those providing basic care; Level 2 represents facilities with specialty care; and Level III, facilities with subspecialty care (24). Information on hospital level was either missing (0.05%) or other (0.15%) in 0.20% of records.

Race/ethnicity was obtained from the birth and fetal death records and defined by five categories: 1) Hispanic; 2) non-Hispanic white; 3) non-Hispanic black; 4) Asian/Pacific Islander; 5) Native/American Aleutian. Race/ethnicity information was missing 0.19% of records.

Maternal age at delivery was obtained from the birth and fetal death records as a continuous variable. The mean age of women in the study was 29.7 years with a standard deviation of 6.06 and ranges from 10-61 years. There was 0.00001% missing data for this variable. For analytic purposes and to align with previous studies, maternal age was defined as five dichotomous variables based on six groups: <20 years, 20-24 years, 25-29 years, 30-34 years, 35-39 years, and 40+ years, with the reference group of 25-29 years.

Maternal education was obtained from birth certificate and fetal death records. Data was collected differently for 2000-2010 and 2011-2012 due to the adoption of the 2003 US Standard Certificate of Live Birth in 2011. This variable was defined by four categories: college or more, some college, high school graduate, or less than high school. College or more was derived from "Bachelor's" or "Post-Graduate" coding for the 2000-2010 maternal degree variable and "Bachelor's Degree," "Master's Degree," or "Doctorate or Professional Degree" in the 2011-2012 data. Some college was defined based on "Associate" or "Certificate/other" coding in the 2000-2010 maternal degree data and "Some college credit but no degree," and "Certificate," or "Associate Degree" in the 2011-2012 data. High school graduation was "High school" or "GED," in maternal diploma coding or "12 years of education" in the years of maternal education variable from the 2000-2010 records and the "High school graduate or GED completed" maternal education variable in 2011-2012. Less than high school was defined by "No high school" in the maternal diploma category in 2000-2010 data and "8^{th} grade or less" or "9^{th}-12^{th} grade, no diploma" in the 2011-2012 data. If there was no information, the variable was then coded as missing (0.27% of data). High school was assigned as the reference category.

Payer source was informed by both the hospital delivery discharge record and the birth certificate and fetal death records to capture the insurance payer source at delivery. Payer source was a categorical variable with four categories: private, public, self-pay, and free care. When both sources agreed on delivery payer (86.2% of deliveries), then the payer source was so assigned. If they did not agree, payer source was defined hierarchically, first by any indication in either source of public, then self-pay, then free care, then private. If there was no information in either data source, the variable was then categorized as missing (0.00004%). Private insurance at delivery was the most common type and assigned as the reference category.

Cigarettes during pregnancy information was obtained from birth certificate and fetal death records, were assessed differently assessments in 2000-2010 and 2011-2012. In 2000-2010, tobacco use during pregnancy was measured by the number of cigarettes per day in the year prior to pregnancy and during pregnancy. In 2011-2012, the question asked about smoking by trimester, including the three months prior to pregnancy. To ensure comparability across years, smoking was measured as a dichotomous variable to capture any smoking during pregnancy. From 2000-2010, any non-zero value indicated smoking during pregnancy as did any non-zero value in any trimester from 2011-2012. There was 0.18% missing data for this variable. No smoking during pregnancy was assigned as the reference category.

Marital status was obtained from birth certificate and fetal death records to indicate status at delivery. Marital status had three categories: married, not married, or previously married within 300 days of birth. To align with previous research, this variable was defined as a dichotomous, married and not married; the latter included the previously

married category. Not married was the reference category and there was 0.02% missing data.

Parity was obtained from birth certificate and fetal death records to include previous pregnancies carried to a viable gestational age. It is calculated from the number of previous live births and previous fetal deaths plus one. The mean parity was 1.9 with a standard deviation of 1.1. For analytic purposes this variable was defined by three categories, parities one, two, and three or more, with primiparity as the reference group. There was 0.49% missing data for this variable.

Prenatal care was obtained from birth certificate and fetal death records from the variable assessing the month prenatal care began. The mean month of prenatal care initiation was 2.9 months with a standard deviation of 1.3. To align with previous studies, this variable was categorized by no PNC and 1^{st}, 2^{nd} and 3^{rd} trimester initiation. There was 1.26% missing data for this variable. Prenatal care initiation in the 1^{st} trimester of pregnancy was the reference group.

Plurality was obtained from birth certificate and fetal death records to capture the number of fetuses in the pregnancy. The mean was 1.02 with a standard deviation of 0.16 and range of 1-5 gestations. This variable was defined by three categories: singleton delivery, twin delivery, triplet delivery or greater. There were no missing data for this variable. The reference category was a singleton delivery.

Maternal cardiac disease was obtained from both birth certificate and fetal death records and the hospital delivery discharge ICD-9-CM diagnosis coding. If cardiac disease was indicated on the birth certificate or fetal death record or any ICD-9-CM codes were listed

in the fifteen potential hospital delivery discharge record (Codes: 746.84, 746.86, 746.89, 746.9, V13.65), then maternal cardiac disease was defined as present; if no indication, it was considered to be absent; as a result, there was no missing data for this indicator. No cardiac disease was the reference group for this variable.

Low birth weight delivery was based on the birthweight at time of delivery reported on birth certificate and fetal death records. Low birthweight (LBW) was defined as any delivery less than 2500 grams. In cases of multiple deliveries, any LBW delivery was coded as a LBW. There was 0.43% missing data for this variable. The reference category was a non-LBW delivery.

Method of Delivery was obtained from both the hospital delivery discharge record and the birth certificate and fetal death records and defined by four categories: vaginal, vaginal birth after cesarean (VBAC), cesarean, and repeat cesarean delivery. Data from both sources agreed in 83.48% of deliveries. Data was available from only one data source in 13.24% of deliveries. In the remaining deliveries with discordant information, data from the hospital discharge record was used. There was 0.07% missing records for this variable. Vaginal deliveries were used as the reference group.

Length of stay at delivery hospitalization was obtained from the hospital delivery discharge record. Stays between 1-2 days were the referent category. **Table 3.4** shows each variable.

Table 3.4 Covariates, Data Sources and Coding

Proximate and distal factors			
Aim	**Variable**	**Source**	**Numeric/Categorical Response Categories**
1,2,3	Year of delivery	Linkage	Aim 1: 1: 2000-2002 (reference) 2: 2003-2006, 3: 2007-2009, 4: 2010-2012, Aims 2-3: 1: 2002-2003 (reference), 2: 2004-2005, 3: 2006-2007, 4: 2008-2009, 5: 2010-2011
1,2,3	Hospital Level	BC, FD, HDD	1: Level I, 2: Level II, 3: Level III (reference),
1,2,3	Race/ethnicity	BC, FD	1: Hispanic, 2: non-Hispanic white (reference), 3: non-Hispanic black, 4: Asian/Pacific Islander, 5: Native American or Other
1,2,3	Maternal age at delivery (years)	BC, FD	1: <20, 2: 20-24, 3: 25-29 (reference) 4: 30-34, 5: 35-39, 6: 40+
1,2,3	Maternal education	BC,FD	1: None, 2: HS or GED (reference), 3: Some college, 4: College or above
1,2,3	Overall payer source	BC,FD, Hospital Discharge (HD)	1: Private (reference), 2: Public, 3: Self-pay, 4: Free care
1,2,3	Cigarettes daily during pregnancy	BC FD	0: None (reference), 1: Any
1,2,3	Marital status	BC,FD	0: Unmarried (reference), 1: Married
1,2,3	Parity		1: 1 (reference), 2: 2, 3: 3+
1,2,3	Trimester of prenatal care initiation	BC,FD	0: None 1: 1st trimester (reference), 2: 2nd trimester, 3: 3rd trimester
1,2,3	Plurality	BC,FD	1: Singletons (reference),

			2: Twins, 3: Triplets or more
1,3	Cardiac disease	BC, FD, HDD	1: BC flag or ICD-9 code for congenital cardiac disease: 746.84, 746.86, 746.89, 746.9, V13.65; 0: Otherwise, no (reference)
Morbidity at delivery			
1,2,3	Low Birthweight delivery (grams)	BC, FD	0: ≥2500g (reference) 1: <2500 grams,
1,2,3	Method of Delivery	BC, FD, HDD	1: Vaginal (reference) 2: Vaginal Birth After Cesarean, 3: Primary cesarean, 4: Repeat cesarean
1,2,3	Severe maternal morbidity	HDD	See Table 3. for full ICD-9-CM coding
1,2,3	Length of stay at delivery	HDD	1: 1-2 days (reference), 2: 3-4 days, 3: 5+ days
2,3	Type of stay	HD, ED, OS	HD: 1: HD flag, 0: Otherwise OS: 1: OS flag; 0: Otherwise ED: 1: ED flag; 0: Otherwise
2,3	Principal condition present	HD, ED, OS	ICD-9-CM coding to inform other variables
2,3	Principal diagnosis code	HD, ED, OS	ICD-9-CM coding to inform other variables
2,3	Principal procedure code	HD	ICD-9-CM coding to inform other variables
2,3	Diagnosis codes	HD, OS, ED	ICD-9-CM coding (15 fields HD; 6 fields OS; 6 fields ED)
2,3	Procedure codes	HD, OS, ED	ICD-9-CM coding (15 fields HD; 6 fields OS; 6 fields ED)
2,3	Admission date	HDD, HD, OS, ED	Date
2,3	Discharge date	HDD, HD, OS, ED	Date
2,3	Date of death	Death	Date

Data Evaluation

The Massachusetts birth certificate prior to 2011 did not include a field for maternal weight or height; therefore, the only consistent source for obesity data was the ICD-9-CM coding on the delivery hospitalization for the entire study period. If obesity was listed as an ICD-9–CM code during the delivery hospitalization, the variable was coded as dichotomous, obese versus non-obese. Analyses were conducted with post-2011 data to examine obesity from data on the birth certificate for the maternal height and weight variables compared to obesity codes captured in the hospital discharge data. This

analysis revealed limited validity of the obesity data on the hospital delivery discharge record. Comparisons of information from ICD-9-CM coding in the hospital delivery discharge record and birth certificate data in 2011-2012 were inconsistent with only a 16.6% match of ICD-9-CM obesity coding in 2011-2012 to the obesity measure derived from the height and weight data in the birth certificate records; therefore, obesity was not included in analyses.

Missing data was also evaluated for the variables when possible. For variables informed only by ICD-9-CM diagnosis or procedure codes, investigations into missingness were not feasible; if a code was not present on any of the diagnosis and/or procedure codes, it was considered absent, not missing. Variables from the birth certificate, with the exception of prenatal care initiation, had missing values for less than one percent of records; missingness ranged from 0.00001% (maternal age) to 1.26% (prenatal care trimester of initiation). Due to the low prevalence of missingness across the data, multiple imputation was not considered (25), and deliveries with missing data were excluded in multivariate analyses. For multivariate analyses, in Aim 1, 97.8% of observations were used (n=940,982); in Aim 2, 99.0% of observations were used (n=678,677); and in Aim 3, 98.3% of all observations were used (n=723,061).

Statistical Methods

Aim 1

The analysis of data involved several steps, the first of which was descriptive. Frequencies of each category of hypertension and chronic conditions were estimated by delivery hospitalization and examined for trends over the study period. Similarly, the criteria defining SMM based on ICD-9-CM codes were applied and frequencies of the

contributing diagnoses and procedures to SMM were estimated and examined over the study period. The prevalence of subcategories of hypertensive disorders in pregnancy and the rate of SMM for each was then estimated. Metric covariates, such as maternal age, were categorized based on clinically meaningful and interpretable cut points informed by previous research. The prevalence of hypertensive disorders in pregnancy was then described by social and biological characteristics.

Bivariate relations between maternal hypertensive disorders in pregnancy and SMM with the social and biological covariates were examined using Wald χ^2 tests. Significant changes in trends over time were assessed through Cochrane-Armitage tests. For all analyses, statistical significance was assessed at $p \leq 0.05$. *A priori* confounders from the conceptual model included were: maternal age, race/ethnicity, maternal education, insurance delivery payer, calendar time, hospital size, prenatal care initiation, parity, plurality, current LBW weight delivery, smoking during pregnancy, cardiac disease, and marital status. Of particular interest was the relation between chronic conditions, hypertensive disorders, and severe maternal morbidity. Additional variables that were significant in Wald tests were included initially in the multivariable analyses.

Logistic multivariable regression models of SMM with and without blood transfusion used a generalized estimating equations (GEE) approach to account for multiple deliveries by the same woman over the study period. The GEE approach is an alternative to maximum likelihood (ML) estimation that allows for analyzing correlated responses by incorporating the covariance matrix of the vector of responses (26). Adjusted odds ratios of SMM for hypertensive disorders in pregnancy as well as other chronic conditions were estimated along with 95% confidence intervals. A second model

examined the outcome of cardiac-specific SMM, using the same methods as described above. *A priori* interaction terms were proposed to examine relations between hypertensive disorders with other chronic and pregnancy-associated conditions, age, and race/ethnicity.

Model fit was assessed using quasi-likelihood scores and multicollinearity by variance inflation factors on a linear multivariable regression model (27, 28). The correlation of outcomes among women with multiple deliveries over the study period was examined through matrices. Exchangeable ($r_{ij,ij'} = p, j \neq j'$), autoregressive ($r_{ij,ij'} = p^{|t_{ij} - t_{ij'}|}$), and unstructured ($r_{ij,ij'} = \rho_{jj'}$) matrices were explored to model within subject correlation. All analyses were performed sequentially using SAS 9.3 (Cary, NC). An example of a model estimated for Aim 1 is shown below.

<u>Example: Logistic Regression Model with GEE Approach of Severe Maternal Morbidity (SMM) with chronic hypertension as a predictor of interest</u>

Let $Y_{ij} = 1$ if the j^{th} delivery had severe maternal morbidity in the i^{th} woman, and $Y_{ij} = 0$ otherwise.

$$Log\left\{\frac{\Pr(Y_{ij}=1)}{\Pr(Y_{ij}=0)}\right\} = \beta_0 + \beta_1 ChronicHTN_{ij} + \beta_2 GestHTN_{ij} + \beta_3 MPE_{ij} + \beta_4 SPE_{ij} + \beta_5 SIPE_{ij} + \beta_6 Age_{ij} + \beta_7 Race_i \ldots + \beta_p X_{pij} + \varepsilon_{ij}$$

where:

$Log\left\{\frac{\Pr(Y_{ij}=1|b_{i1},b_{i2})}{\Pr(Y_{ij}=0|b_{i1},b_{i2})}\right\}$ = average log odds of SMM at delivery across women;

β_0 = log odds of SMM at delivery for women without a diagnosis of hypertension in pregnancy (coded as 0) and with all other variables in the referent category;

β_1 = difference in log odds of SMM at delivery for women with chronic hypertension (coded as 1) versus women without chronic hypertension (coded as 0), adjusting for all other variables in the equation; and

$\varepsilon_{ij} \sim N(0, \sigma^2)$.

The odds ratio of SMM at delivery for women with chronic hypertension versus those without chronic hypertension adjusting for all other variables in the equation was calculated through e^{β_1}.

Aim 2

In Aim 2, the population was restricted to women without chronic medical conditions, specifically asthma, autoimmune conditions, chronic hypertension and pre-exiting diabetes, based on results from Aim 1. Exploratory data analyses were first conducted to understand the relation between SMM at delivery and hospitalization in the year postpartum. Analyses first described all one year and six week postpartum hospital encounters by visit and by delivery over the study period. Injury- and antenatal-related encounters were described and then excluded from further analysis. Exploratory analyses also examined deliveries to women who died during the first year post-delivery and when they died; sensitivity analyses considered exclusion of maternal death. Analyses described the type of postpartum hospital encounter by number, postpartum timing, and primary diagnoses. The first three digits of the ICD-9-CM principal diagnosis codes were extracted for each type of encounter to describe the main causes of hospital utilization. Next, analyses assessed each type of encounter within six weeks and one year by SMM. Bivariate relations between SMM and at least one hospital encounter with the social and biological variables were examined through Wald χ^2 tests. Trends over time were assessed through Cochrane-Armitage tests. All analyses used significance $p \leq 0.05$.

Log-binomial multivariable regression models of the relation of SMM with hospital encounters were estimated using a GEE approach to account for multiple

deliveries by the same woman over the study period. These models were adjusted for a priori and statistically significant confounders from the bivariate analyses. The log link required for log-binomial regression initially did not converge in multivariable regression models, as the link does not ensure that predicted probabilities are mapped to the [0,1] range that is required for probabilities; to assure convergence of the multivariable log-binomial regression models, a negative intercept of 4 was used to start estimation as suggested in previous research (29).

Model fit and selection was informed through quasi-likelihood statistics (QIC), which is analogous to Akaike Information Criterion (AIC) statistics when using a generalized estimating equations (GEE) approach (28). Multicollinearity was assessed through variance inflation factors (VIF) on a linear regression scale; variables were considered for exclusion from the model if the mean VIF was greater than 10 (27). Previous analyses informed within-subject correlation of outcomes over the study period through correlation matrices. Sensitivity analyses examined SMM with and without blood transfusion as well as SMM categorized by total number of indicators (0, 1, 2+).

<u>Example: Log Binomial Regression Model with GEE Approach of Hospital Readmission within Six Weeks with Severe Maternal Morbidity (SMM) as a predictor of interest</u>

Let $Y_{ij} = 1$ if the j^{th} delivery had a hospital readmission within six weeks postpartum in the i^{th} woman, and $Y_{ij} = 0$ otherwise.

$$Log\big(\Pr(Y_{ij} = 1|b_{i1}, b_{i2})\big) = \beta_0 + \beta_1 SMM_{ij} + \beta_2 Age_{ij} + \beta_3 Race_i \ldots + \beta_p X_{pij} + \varepsilon_{ij}$$

where:

$Log\big(\Pr(Y_{ij} = 1|b_{i1}, b_{i2})\big)$ = average log risk of hospital discharge record within six weeks postpartum across women;

$\beta_0 =$ log relative risk of hospital readmission within six weeks postpartum without SMM (coded as 0) and with all other variables in the referent category;

$\beta_1 =$ difference in log risks of hospital readmission within six weeks postpartum for women with SMM at delivery (coded as 1) versus women without SMM at delivery (coded as 0), adjusting for all other variables in the model; and

$\varepsilon_{ij} \sim N(0, \sigma^2)$.

The relative risk of hospital readmission within six weeks postpartum for women with SMM at delivery versus women without SMM at delivery adjusting for all other variables in the model was calculated through e^{β_1}.

Aim 3

For Aim 3, women with chronic medical conditions were included in the study population to capture all deliveries to MA resident women from 2002-2011 and capture all non-injury and non-antenatal-related postpartum rehospitalizations within one year. As described in Aim 2, preliminary analyses described the overall rate of hospitalization for each type of encounter within six weeks and one year by delivery. The prevalence of each type of rehospitalization within the first six weeks and one year post-delivery was then described by maternal hypertensive disorders and SMM at delivery. Measures of SMM and hospital encounters were compared by a priori confounders from the conceptual model in bivariate analyses through chi-square tests; they included social and biological confounders listed in previous aims. Variables that were significant in Wald tests ($p<0.05$) were included initially in the multivariable analyses.

Modified Poisson regression models were used for multivariable analyses with a generalized estimating equations approach, after initial log-binomial regression models failed to converge (30). The main exposures were hypertensive disorders and other

chronic and pregnancy-associated conditions as in Aim 1 as well as SMM as in Aim 2. The main dependent variable was hospitalization by type (hospital discharge, observational stay, emergency department) within both six weeks and one year postpartum. Interactions were evaluated to determine if SMM at delivery modified the relation between maternal hypertensive disorders, as categorized in Aim 1, and postpartum hospital utilization, with significance assessed at $p < 0.05$. Stratified analyses by SMM examined if there were differences in the risk of rehospitalization on maternal hypertensive disorder subtypes.

Sensitivity analyses examined SMM with and without blood transfusion as well as SMM categorized by total number of indicators (0, 1, 2+). Sensitivity analyses also examined whether SMM mediated the relation between maternal hypertensive disorders and rehospitalization. These regression models provided adjusted relative risks for hospital encounters within six weeks and one year postpartum with 95% confidence intervals estimated for exposures of interests.

<u>Example: Poisson Regression Model with GEE Approach of Hospital Readmission within Six Weeks with chronic hypertension as a predictor of interest</u>

Let $Y_{ij} = 1$ if the j^{th} delivery had a hospital readmission within six weeks postpartum in the i^{th} woman and $Y_{ij} = 0$ otherwise.

$$Log\left(\Pr(Y_{ij} = 1|b_{i1}, b_{i2})\right) = \beta_0 + \beta_1 ChronicHTN_{ij} + \beta_2 GestHTN_{ij} + \beta_3 MPE_{ij} + \beta_4 SPE_{ij} + \beta_5 SIPE_{ij} + \beta_6 Race_i + \beta_7 Age_{ij} \ldots + \beta_p X_{pij} + \varepsilon_{ij}$$

where:

$Log\left(\Pr(Y_{ij} = 1|b_{i1}, b_{i2})\right)$ = average log risk of hospital readmission within six weeks postpartum across women;

β_0 = log relative risk of hospital readmission within six weeks postpartum without chronic hypertension (coded as 0) and with all other variables in the referent category;

$\beta_1 =$ difference in log risks of hospital readmission within six weeks postpartum for women with chronic hypertension (coded as 1) versus women without chronic hypertension (coded as 0), adjusting for all other variables in the model; and

$\varepsilon_{ij} \sim N(0, \sigma^2)$.

The relative risk of hospital readmission within six weeks postpartum for women with chronic hypertension versus women without chronic hypertension adjusting for all other variables in the model was calculated through e^{β_1}.

References

1. Yasmeen S, Romano PS, Schembri ME, Keyzer JM, Gilbert WM. Accuracy of obstetric diagnoses and procedures in hospital discharge data. Am J Obstet Gynecol. 2006;194(4):992-1001. Epub 2006/04/04.

2. Declercq E, Barger M, Cabral HJ, Evans SR, Kotelchuck M, Simon C, et al. Maternal outcomes associated with planned primary cesarean births compared with planned vaginal births. Obstet Gynecol. 2007;109(3):669-77. Epub 2007/03/03.

3. Callaghan WM, Creanga AA, Kuklina EV. Severe maternal morbidity among delivery and postpartum hospitalizations in the United States. Obstet Gynecol. 2012;120(5):1029-36. Epub 2012/10/24.

4. Callaghan WM, Mackay AP, Berg CJ. Identification of severe maternal morbidity during delivery hospitalizations, United States, 1991-2003. Am J Obstet Gynecol. 2008;199(2):133 e1-8. Epub 2008/02/19.

5. Kuklina EV, Meikle SF, Jamieson DJ, Whiteman MK, Barfield WD, Hillis SD, et al. Severe obstetric morbidity in the United States: 1998-2005. Obstet Gynecol. 2009;113(2 Pt 1):293-9. Epub 2009/01/22.

6. Main EK, Abreo A, McNulty J, Gilbert W, McNally C, Poeltler D, et al. Measuring severe maternal morbidity: validation of potential measures. Am J Obstet Gynecol. 2015. Epub 2015/11/20.

7. Creanga AA, Bateman BT, Kuklina EV, Callaghan WM. Racial and ethnic disparities in severe maternal morbidity: a multistate analysis, 2008-2010. Am J Obstet Gynecol. 2014;210(5):435 e1-8. Epub 2013/12/04.

8. Savitz DA, Danilack VA, Elston B, Lipkind HS. Pregnancy-induced hypertension and diabetes and the risk of cardiovascular disease, stroke, and diabetes hospitalization in the year following delivery. Am J Epidemiol. 2014;180(1):41-4. Epub 2014/06/01.

9. Creanga AA, Berg CJ, Syverson C, Seed K, Bruce FC, Callaghan WM. Pregnancy-related mortality in the United States, 2006-2010. Obstet Gynecol. 2015;125(1):5-12. Epub 2015/01/07.

10. Hoyert DL. Maternal mortality and related concepts. Vital Health Stat 3. 2007(33):1-13. Epub 2007/04/28.

11. Nannini A, Lazar J, Berg C, Tomashek K, Cabral H, Barger M, et al. Injury: a major cause of pregnancy-associated morbidity in Massachusetts. J Midwifery Womens Health. 2008;53(1):3-10. Epub 2008/01/01.

12. Kuklina EV, Callaghan WM. Cardiomyopathy and other myocardial disorders among hospitalizations for pregnancy in the United States: 2004-2006. Obstet Gynecol. 2010;115(1):93-100. Epub 2009/12/23.

13. Campbell KH, Savitz D, Werner EF, Pettker CM, Goffman D, Chazotte C, et al. Maternal morbidity and risk of death at delivery hospitalization. Obstet Gynecol. 2013;122(3):627-33. Epub 2013/08/08.

14. Kestenbaum B, Seliger SL, Easterling TR, Gillen DL, Critchlow CW, Stehman-Breen CO, et al. Cardiovascular and thromboembolic events following hypertensive pregnancy. Am J Kidney Dis. 2003;42(5):982-9. Epub 2003/10/29.

15. Lydon-Rochelle MT, Holt VL, Cardenas V, Nelson JC, Easterling TR, Gardella C, et al. The reporting of pre-existing maternal medical conditions and complications of pregnancy on birth certificates and in hospital discharge data. Am J Obstet Gynecol. 2005;193(1):125-34. Epub 2005/07/16.

16. Lain SJ, Hadfield RM, Raynes-Greenow CH, Ford JB, Mealing NM, Algert CS, et al. Quality of data in perinatal population health databases: a systematic review. Med Care. 2012;50(4):e7-20. Epub 2011/05/28.

17. Kuklina EV, Ayala C, Callaghan WM. Hypertensive disorders and severe obstetric morbidity in the United States. Obstet Gynecol. 2009;113(6):1299-306. Epub 2009/05/23.

18. The National Center for Health Statistics (NCHS) tCfMaMSC. International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM). [cited 2015 January]; Available from: http://www.cdc.gov/nchs/icd/icd9cm.htm.

19. Savitz DA, Danilack VA, Engel SM, Elston B, Lipkind HS. Descriptive epidemiology of chronic hypertension, gestational hypertension, and preeclampsia in New York State, 1995-2004. Matern Child Health J. 2014;18(4):829-38. Epub 2013/06/25.

20. Fridman M, Korst LM, Chow J, Lawton E, Mitchell C, Gregory KD. Trends in maternal morbidity before and during pregnancy in California. Am J Public Health. 2014;104 Suppl 1:S49-57. Epub 2013/12/21.

21. Thomas SL, Griffiths C, Smeeth L, Rooney C, Hall AJ. Burden of mortality associated with autoimmune diseases among females in the United Kingdom. Am J Public Health. 2010;100(11):2279-87. Epub 2010/09/25.

22. Walley AY, Paasche-Orlow M, Lee EC, Forsythe S, Chetty VK, Mitchell S, et al. Acute care hospital utilization among medical inpatients discharged with a substance use disorder diagnosis. J Addict Med. 2012;6(1):50-6. Epub 2011/10/08.

23. Walley AY, Tetrault JM, Friedmann PD. Integration of substance use treatment and medical care: a special issue of JSAT. J Subst Abuse Treat. 2012;43(4):377-81. Epub 2012/10/20.

24. Obstetricians ACo, Gynecologists. Levels of maternal care. Obstetric care consensus no. 2. Obstetrics and Gynecology. 2015;125(2):502-15.

25. Dong Y, Peng CY. Principled missing data methods for researchers. Springerplus. 2013;2(1):222. Epub 2013/07/16.

26. Fitzmaurice GM, Laird NM, Ware JH. Applied longitudinal analysis: John Wiley & Sons; 2012.

27. O'brien RM. A caution regarding rules of thumb for variance inflation factors. Quality & Quantity. 2007;41(5):673-90.

28. Pan W. Akaike's information criterion in generalized estimating equations. Biometrics. 2001;57(1):120-5.

29. Deddens JA, Petersen MR, Lei X. Estimation of prevalence ratios when PROC GENMOD does not converge. SAS User Group International (SUGI) Proceedings, Seattle, Washington. 2003:270-28.

30. Zou G. A modified poisson regression approach to prospective studies with binary data. Am J Epidemiol. 2004;159(7):702-6. Epub 2004/03/23.

Chapter Four: Results

Overview

This chapter describes the findings for each study aim: 1) Evaluate the relation of maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with severe maternal morbidity at delivery; 2) Evaluate the relation between severe maternal morbidity at delivery and postpartum maternal rehospitalization in the year following delivery among deliveries to women without chronic medical diseases; and 3) Evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with postpartum maternal rehospitalization in the year following delivery, independent of severe maternal morbidity at delivery.

This chapter begins with a description of the study populations for the three aims, followed by a description of the main dependent variables in these analyses, severe maternal morbidity (SMM) at delivery and hospital utilization in the first six weeks and year postpartum. Next, for each study aim, the bivariate and confounder analyses will be presented, followed by the main multivariate results and sensitivity analyses.

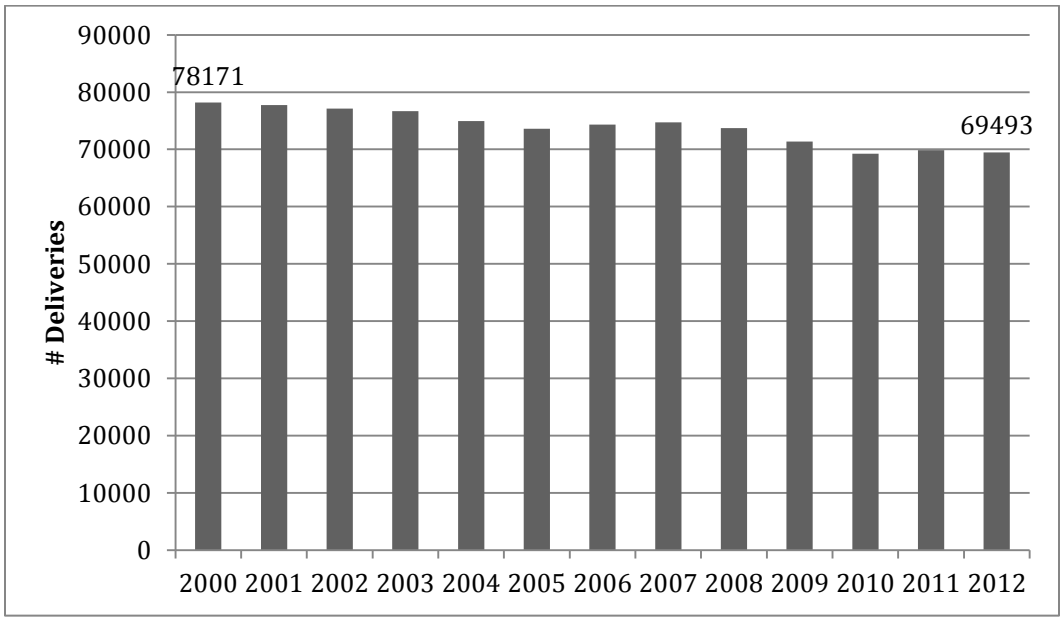
Study Sample

Aim 1

During 2000-2012, there were 980,962 deliveries to resident women in Massachusetts with linked birth certificate/fetal death records and hospital delivery discharge records. Deliveries decreased 11.1% over the study period, from 78,171 in 2000 to 69,493 in 2012 (**Figure 4.1**). These linked deliveries represented 99.0% of resident deliveries in the state. The 980,962 deliveries were to 642,874 unique women;

60.8% of these women had one delivery over the study period and 39.2% had two or more deliveries.

Figure 4.1 Linked Deliveries by Year, MA women 2000-2012



The characteristics of the study sample for all aims are shown in **Table 4.1**. The majority of deliveries across all aims were to women 25-34 years of age (56%), non-Hispanic white women (68%), with at least a high school education (89%), who were privately insured (60%) and who were married (68%). Just under half of deliveries were to primiparous women (45%) and almost all were singleton deliveries (98%). Most deliveries occurred to women who received prenatal care in the first trimester (83%) and did not smoke cigarettes during pregnancy (92-93%). More than four in ten deliveries were at Level III hospitals (42-43%) and 7% were a low birth weight (LBW) delivery.

Table 4.1 Descriptive Characteristics in Study Populations by Aim

Characteristic	Aim 1 Deliveries 2000-2012	Aim 2 Deliveries 2002-2011 excluding specific chronic conditions	Aim 3 Deliveries 2002-2011
	Overall %, N (N=960,982)	Overall %, N (N=685,228)	Overall %, N (N=735,576)
Maternal age (years)			
<20	6.0 (57,791)	6.0 (41,138)	6.0 (44,281)
20-24	15.7 (150,521)	15.9 (107,760)	15.8 (116,500)
25-29	24.1 (231,915)	24.2 (166,122)	24.1 (177,262)
30-34	31.8 (305,971)	31.6 (216,818)	31.5 (231,794)
35-39	18.2 (174,438)	18.1 (124,066)	18.2 (134,147)
40+	4.2 (40,332)	4.1 (28,312)	4.3 (31,579)
Race/ethnicity			
Hispanic	14.1 (135,354)	14.0 (96,025)	14.2 (104,231)
NH White	68.2 (654,112)	68.0 (465,374)	67.8 (497,867)
NH Black	8.4 (80,992)	8.2 (56,105)	8.6 (62,854)
Asian/PI	7.4 (70,618)	7.8 (53,078)	7.5 (54,984)
Am. Indian/Other	1.9 (18,054)	2.0 (13,614)	2.0 (14,532)
PNC month initiation			
No PNC	0.3 (3011)	0.3 (2,199)	0.3 (2,355)
1st trimester	83.0 (787,587)	82.8 (561,014)	82.9 (602,801)
2nd trimester	13.9 (131,968)	14.1 (95,215)	14.0 (101,780)
3rd trimester	2.8 (26,270)	2.8 (19,072)	2.8 (20,233)
Parity			
1	45.2 (432,364)	45.4 (309,709)	45.3 (331,982)
2	35.3 (327,524)	34.5 (235,409)	34.3 (251,482)
3+	20.5 (196,386)	20.1 (137,098)	20.3 (148,900)
Plurality			
Singleton	97.7 (938,830)	97.7 (669,570)	97.7 (718,355)
Twins	2.2 (21,430)	2.2 (15,168)	2.3 (16,680)
Triplets +	0.1 (722)	0.1 (490)	0.1 (541)
Education			
<HS	10.8 (103,727)	10.7 (73,430)	10.8 (79,236)
HS/GED	36.3 (347,955)	36.8 (251,618)	37.0 (271,803)
Some college	11.2 (107,352)	10.0 (68,007)	10.1 (73,783)
Bachelors +	41.7 (399,306)	42.5 (290,664)	42.1 (309,108)
Cigarette Use during Pregnancy			
No	92.3 (885,223)	92.8 (634,555)	92.6 (680,114)
Yes	7.7 (74,051)	7.2 (49,551)	7.4 (54,268)
Hospital Level			
Level 1	19.4 (185,804)	19.9 (135,866)	19.5 (142,905)
Level 2	37.7 (361,866)	38.0 (259,904)	37.2 (272,734)
Level 3	42.9 (411,491)	42.1 (288,111)	43.4 (318,530)
Method of Delivery			
Vaginal	67.5 (647,996)	67.3 (461,001)	66.6 (489,698)
VBAC	2.4 (22,684)	2.1 (14,499)	2.1 (15,516)
Primary C-section	18.0 (173,106)	18.3 (124,987)	18.7 (137,193)
Repeat C-section	12.1 (116,492)	12.3 (84,077)	12.6 (92,481)
Marital Status			
Married at delivery	68.3 (656,183)	68.2 (466,875)	67.7 (497,673)

Not married	31.7 (304,617)	31.9 (218,210)	32.3 (237,747)
Insurance Delivery Payer			
Private	60.2 (578,765)	60.1 (411,556)	59.7 (439,103)
Public	37.7 (361,800)	38.1 (264,280)	38.5 (283,008)
Free care	1.1 (10,341)	1.0 (6,776)	1.0 (7,372)
Self-pay	1.0 (10,037)	0.8 (5,584)	0.8 (6060)
Low birth weight			
No	93.2 (891,939)	93.4 (637,625)	93.1 (681,673)
Yes	6.8 (64,929)	6.6 (44,736)	6.9 (50,703)
Diabetes			
Pre-existing diabetes	1.1 (10,951)	--	1.2 (8,747)
Gestational diabetes	5.1 (49,259)	5.0 (34,436)	5.2 (37,989)
None	93.7 (900,772)	95.0 (650,792)	93.7 (688,840)
Asthma	3.4 (32,678)	--	3.5 (25,392)
Depression	2.6 (24,949)	2.5 (16,892)	2.8 (20,475)
Substance use	1.4 (13,250)	1.3 (9,170)	1.4 (10,437)
Autoimmune conditions	0.7 (6,714)	--	0.7 (5,237)
Congenital cardiac disease	0.8 (7,194)		0.7 (5184)

During the study period for Aim 1, 8.7% of deliveries had a reported diagnosis of a maternal hypertensive disorder. Gestational hypertension was the most common form of hypertensive disorder (3.7%), followed by mild preeclampsia (2.0%), chronic hypertension (1.6%), severe preeclampsia (1.1%), and superimposed preeclampsia (0.3%). All maternal hypertensive disorders, with the exception of mild preeclampsia, increased during the study period ($p < 0.0001$ for trend) (**Figure 4.2)**. Overall, any maternal hypertensive disorders increased among deliveries from 7.7% in 2000 to 10.0% in 2012.

The most common maternal chronic conditions among deliveries were asthma (3.4%) and depression (2.6%), followed by substance use disorders (1.4%), pre-existing diabetes (1.2%) and autoimmune conditions (0.7%). Gestational diabetes (5.1%) was the most common pregnancy-associated condition. All chronic conditions and pregnancy-associated conditions increased during the study period ($p<0.0001$ for trend) (**Figure 4.3**).

Figure 4.2 Maternal Hypertensive Disorders by Year, Deliveries to MA Women, 2000-2012

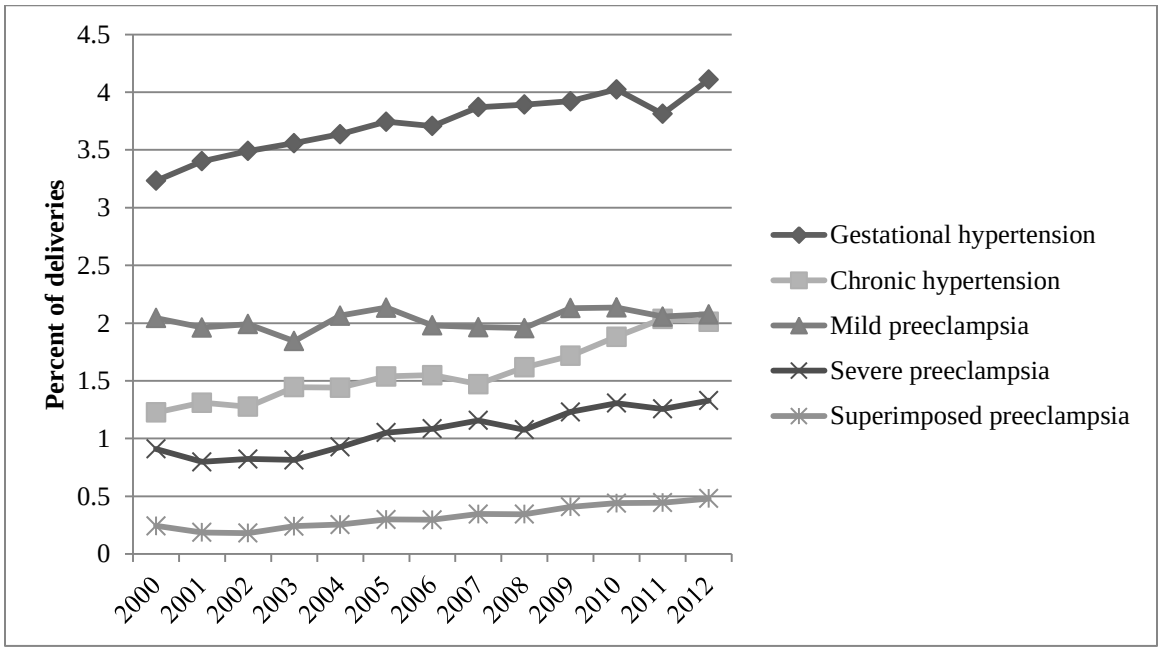
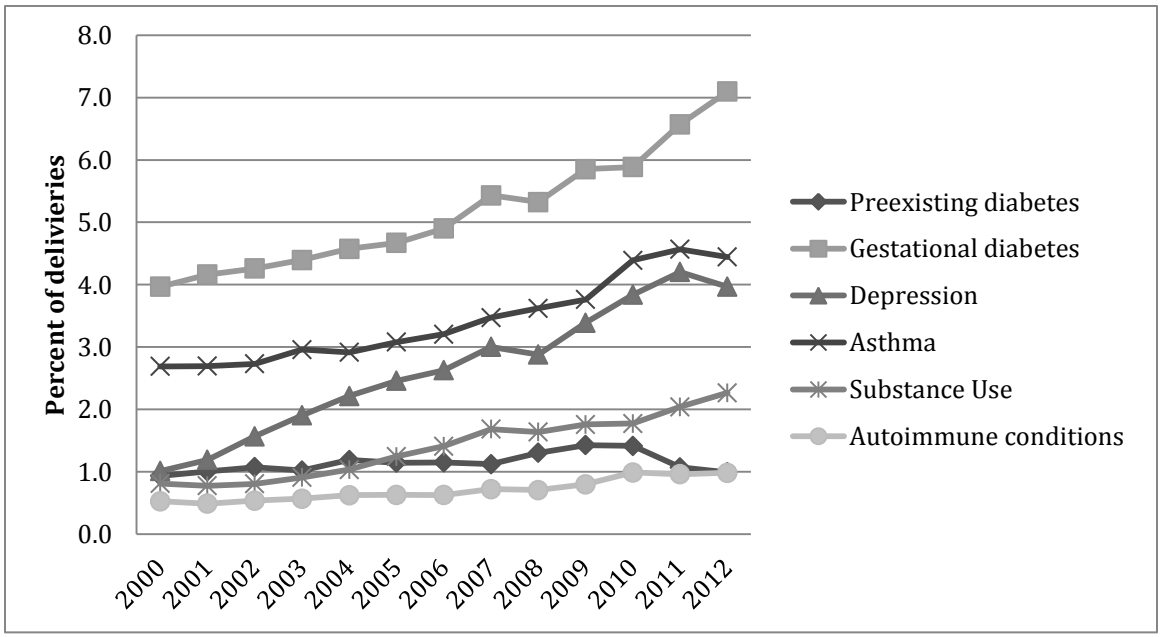


Figure 4.3 Chronic and Pregnancy-Related Conditions by Year, Deliveries to MA Women, 2000-2012



Aim 2

The population for Aims 2 and 3 was confined to years 2002-2011; 2002 was the first year for which all types of postpartum data were available and 2011 was the last year for which follow-up for one year postpartum was possible. There were 735,576 deliveries with linked hospital delivery and birth certificate/fetal death records to resident women in Massachusetts between 2002 and 2011. For Aim 2, deliveries to women with chronic medical conditions prior to pregnancy that were associated with SMM at delivery were excluded from the study population. Based on Aim 1 results, these conditions included: chronic hypertension, superimposed preeclampsia, pre-existing diabetes, autoimmune conditions and asthma, (n=50,348) for a final population for this aim of 685,228. The final population represents 93.2% of the linked birth certificate/fetal death records with hospital delivery discharge data from 2002-2011 and 92.2% of all hospital deliveries.

Descriptive characteristics for deliveries for Aim 2 mirrored those from Aim 1 (**Table 4.1**). The SMM rate was 99 per 10,000 deliveries during the study period; without transfusion, the SMM rate was 43 per 10,000. Both SMM rates increased over the study period ($p<0.0001$ for trend). Among deliveries to women with SMM at delivery, 85.4% had one SMM indicator, 9.6% had two SMM indicators, and 5.1% had two or more SMM indicators.

Aim 3

For Aim 3, all deliveries identified in hospital delivery and birth certificate/fetal death records from 2002-2011 were included for a study population of 735,576. Descriptive characteristics for deliveries for Aim 3 mirrored those from Aim 1 (**Table 4.1**). Maternal hypertensive disorders were present in 8.8% of deliveries to women during

the study period: 3.8% had gestational hypertension, 2.0% had mild preeclampsia, 1.6% had chronic hypertension, 1.1% had severe preeclampsia, and 0.3% had superimposed preeclampsia. Among deliveries with reports of other chronic and pregnancy-associated conditions, 5.2% had gestational diabetes, 3.5% had asthma, 1.2% had preexisting diabetes, and 0.7% had autoimmune conditions.

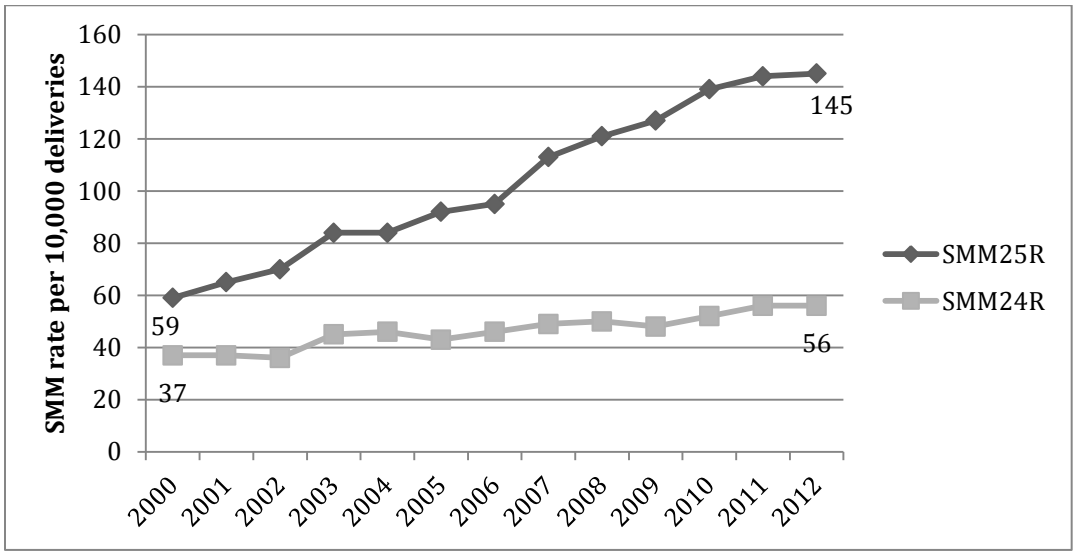
In Aim 3, the rate of SMM at delivery was 106.2 per 10,000 delivery hospitalizations; without transfusion, the rate of SMM at delivery hospitalization was 47.0 per 10,000 delivery hospitalizations.

Aim 1

Dependent Variable: SMM

The overall rate of SMM was 101.9 per 10,000 deliveries. The rate increased from 59 per 10,000 in 2000 to 145 per 10,000 in 2012 (**Figure 4.4**). This rate reflects the recalculation of SMM to consider length of stay by method of delivery. Without this recalculation, the overall SMM rate of all twenty-five indicators was 125.4 per 10,000 deliveries. Excluding blood transfusion, the rate of SMM was 46.0 per 10,000 deliveries across the study period; it also increased significantly during the study period ($p<0.001$). The rate of increase was greater for SMM including transfusion. Without recalculation for length of stay by method of delivery, the SMM rate without blood transfusion was 71.4 per 10,000 deliveries.

Figure 4.4 Rates of Severe Maternal Morbidity with and without Blood Transfusion at Delivery by Year, Deliveries to MA Women 2000-2012



SMM25R: SMM with blood transfusion
SMM24R: SMM without blood transfusion

Table 4.2 shows the percentage of deliveries with each SMM indicator. The most common SMM conditions and procedures were blood transfusion (67.5 per 10,000 deliveries), heart failure (8.6 per 10,000 deliveries), operations on the heart and pericardium (8.4 per 10,000 deliveries), and disseminated intravascular coagulation (8.1 per 10,000 deliveries). The recalculation criteria, which adjusted for length of stay based on method of delivery, had the greatest impact on the indicators of severe anesthesia complications and heart failure during procedure or surgery.

Table 4.2 Severe Maternal Morbidity at Delivery Indicators, Deliveries to MA Women 2002-2012

Classification	% deliveries (n)	Severity Recalculated[1] % deliveries (n)
1. Acute myocardial infarction	0.00 (26)	0.00 (20)
2. Acute renal failure	0.05 (478)	0.04 (358)
3. Adult respiratory distress syndrome	0.03 (331)	0.03 (276)
4. Amniotic fluid embolism	0.00 (40)	0.00 (30)
5. Aneurysm	0.00 (19)	Suppressed[2]
6. Cardiac arrest/ventricular fibrillation	0.01 (54)	0.00 (44)
7. Disseminated intravascular coagulation	0.14 (1378)	0.08 (776)
8. Eclampsia	0.05 (458)	0.03 (283)
9. Heart failure during procedure or surgery	0.21 (1999)	0.09 (830)
10. Internal injuries of thorax, abdomen, and pelvis	0.01 (77)	0.00 (41)

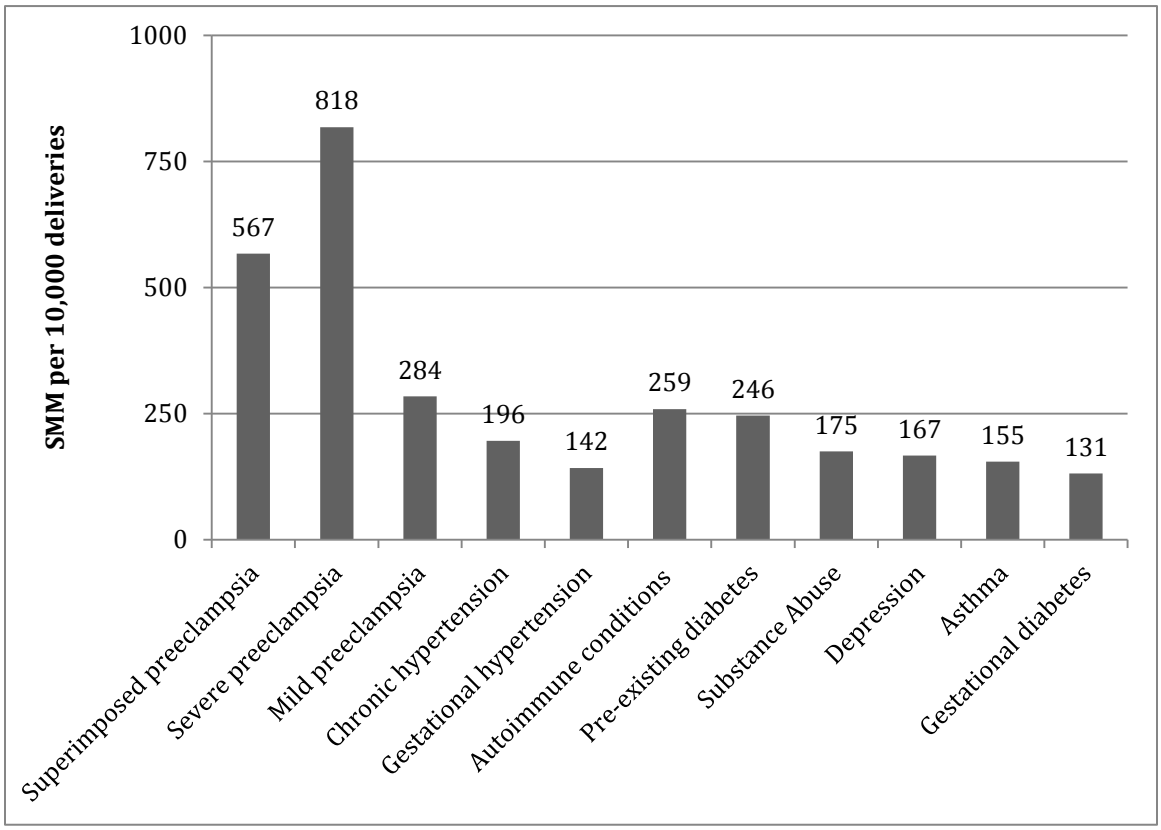
11. Intracranial injuries	Suppressed[2]	Suppressed[2]
12. Puerperal cerebrovascular disorders	0.04 (350)	0.02 (187)
13. Pulmonary edema	0.01 (138)	0.01 (108)
14. Severe anesthesia complications	0.02 (224)	0.01 (91)
15. Sepsis	0.02 (278)	0.02 (247)
16. Shock	0.03 (243)	0.02 (178)
17. Sickle cell anemia with crisis	0.01 (79)	0.01 (68)
18. Thrombotic embolism	0.02 (183)	0.02 (150)
19. Blood transfusion	0.67 (6,482)	--
20. Cardio monitoring	0.01 (69)	--
21. Conversion of cardiac rhythm	0.00 (42)	--
22. Hysterectomy	0.07 (676)	--
23. Operations on heart and pericardium	0.08 (807)	--
24. Temporary tracheostomy	0.00 (12)	--
25. Ventilation	0.05 (502)	--
Overall SMM (25 conditions)	1.25 (12,049)	--
SMM (24 conditions; no blood transfusion)	0.71 (6,860)	
SMM 25 recalculated (based on LOS and MOD)		1.02 (9,793)
SMM 24 recalculated (based on LOS and MOD)		0.46 (4,420)

1 Recalculation based on length of stay was not applied to delivery hospitalizations with severe complications identified by procedure codes
2 Cell suppression when <11

Bivariate Results

The highest rate of SMM among deliveries with hypertensive disorders was 817.8 per 10,000 deliveries among deliveries to women with severe preeclampsia, followed by superimposed preeclampsia (567 per 10,000), mild preeclampsia (284 per 10,000), chronic hypertension (196 per 10,000) and gestational hypertension (142 per 10,000). Among deliveries to women with other chronic conditions, the rate of SMM was highest among those with autoimmune conditions (259.2 per 10,000 deliveries), followed by preexisting diabetes, substance use disorders, depression, asthma, and gestational diabetes (**Figure 4.5**).

Figure 4.5 Rate of SMM per 10,000 deliveries by Maternal Hypertensive Disorders and Chronic Conditions before and during Pregnancy, Deliveries to MA Women 2000-2012



Other social and biological characteristics were also associated with SMM at delivery, with all significant in Wald χ^2 statistical tests ($p<0.0001$) (**Table 4.3**). Rates of SMM at delivery were elevated for deliveries to women older than 40 years of age (170.3 per 10,000 deliveries), non-Hispanic black women (178.8 per 10,000), and women with less than high school education (125.5 per 10,000), and who were publicly insured (124.7 per 10,000).

Table 4.3 Severe Maternal Morbidity Rate by Social and Biological Characteristics, Deliveries to MA Women 2000-2012

Characteristic	SMM25 rate per 10,000 deliveries
	Overall 101.7
Maternal age(years)	
<20	109.5

20-24	96.8
25-29	93.4
30-34	90.4
35-39	118.0
40+	170.3
Race/ethnicity	
Hispanic	126.3
Non-Hispanic White	86.0
Non-Hispanic Black	178.8
Asian/Pacific Islander	108.5
American Indian/Other	95.3
PNC month initiation	
No PNC	302.2
1st trimester	97.3
2nd trimester	109.8
3rd trimester	109.6
Parity	
1	108.5
2	82.8
3+	116.5
Plurality	
Singleton	94.6
Twins	389.6
Triplets +	720.2
Education	
<High School	125.5
High School/GED	106.1
Some college	108.9
Bachelors +	87.9
Cigarette Use	
No	102.5
Yes	87.0
Hospital Level	
Level 1	82.9
Level 2	73.0
Level 3	134.5
Method of Delivery	
Vaginal	55.8
VBAC	96.1
Primary C-section	225.8
Repeat C-section	172.8
Marital Status	
Married at delivery	93.1

Not married	119.6
Insurance Delivery Payer	
Private	86.9
Public	124.7
Free care	111.6
Self-pay	114.1

Confounder Results

Table 4.4 shows variation in maternal hypertensive disorders by social and biological characteristics as well as other chronic and pregnancy-associated conditions. With a sample of almost one million deliveries, all Wald χ^2 analyses were significant ($p<0.0001$). Maternal age, education, race/ethnicity, prenatal care initiation, parity, plurality, cigarette use during pregnancy, hospital level, insurance payer, method of delivery, low birth weight delivery, marital status and all chronic and pregnancy-related chronic conditions were significantly associated with maternal hypertensive disorders.

Table 4.4 Prevalence of Maternal Hypertensive Disorders by Social and Biological Characteristics, Deliveries to MA Women 2000-2012

	No HTN[1]	Super-imposed PE[1]	Severe PE[1]	Mild PE[1]	Chronic HTN[1]	Gestational HTN[1]
Overall % (n=960,982)	**91.3**	**0.3**	**1.1**	**2.0**	**1.6**	**3.7**
Maternal age (years)						
<20	92.1	0.1	1.4	2.8	0.4	3.3
20-24	92.4	0.2	1.1	2.2	0.7	3.4
25-29	91.6	0.3	1.0	2.1	1.3	3.9
30-34	91.5	0.3	1.0	1.8	1.6	3.8
35-39	90.6	0.5	1.1	1.9	2.4	3.7
40+	86.6	0.9	1.6	2.4	4.1	4.4
Race/ethnicity						
Hispanic	92.3	0.3	1.3	2.3	1.2	2.5
Non-Hispanic White	91.1	0.3	0.9	2.0	1.5	4.2
Non-Hispanic Black	87.8	0.8	1.9	2.5	3.3	3.7

Asian/PI	95.3	0.2	0.7	1.2	0.7	1.9
Am. Indian/Other	91.7	0.3	1.3	2.3	1.3	3.1
PNC month initiation						
No PNC	90.9	0.7	2.2	2.1	1.9	2.3
1st trimester	91.2	0.3	1.0	2.0	1.6	3.8
2nd trimester	92.1	0.3	1.0	2.0	1.4	3.2
3rd trimester	93.1	0.3	0.9	1.7	1.3	2.8
Parity						
1	89.1	0.3	1.5	2.9	1.4	4.7
2	93.3	0.3	0.7	1.3	1.5	2.9
3+	92.8	0.4	0.7	1.3	2.0	2.9
Plurality						
Singleton	91.9	0.3	1.0	1.9	1.6	3.7
Twins	78.4	0.8	5.0	7.9	2.0	5.9
Triplets +	68.8	0.8	9.6	12.9	2.2	5.7
Education						
<High School	92.7	0.3	1.1	2.0	1.1	2.9
HS/GED	91.1	0.4	1.1	2.2	1.6	3.7
Some college	89.9	0.4	1.1	2.2	2.1	4.2
Bachelors +	91.6	0.3	1.0	1.8	1.5	3.9
Cigarette Use	93.3	0.2	0.6	1.5	1.3	3.0
Hospital Level						
Level 1	92.9	0.2	0.5	1.7	1.3	3.5
Level 2	92.6	0.2	0.7	1.7	1.2	3.7
Level 3	89.5	0.5	1.7	2.5	2.0	3.9
Method of Delivery						
Vaginal	92.9	0.2	0.6	1.7	1.3	3.4
VBAC	95.1	0.2	0.3	0.9	1.4	2.2
Primary C-section	84.8	0.7	3.0	3.9	2.2	5.5
Repeat C-section	91.6	0.5	1.0	1.4	2.5	3.0
Marital Status						
Married at delivery	91.4	0.3	1.0	1.9	1.6	3.8
Not married	91.2	0.3	1.2	2.3	1.5	3.5
Insurance Delivery Payer						
Private	91.1	0.3	1.0	2.0	1.6	4.1
Public	91.8	0.4	1.2	2.1	1.5	3.1
Free care	89.2	0.6	1.4	2.5	2.2	4.2
Self-pay	89.7	0.5	1.3	2.3	2.4	3.7

Low birth weight	77.4	1.9	8.4	5.3	2.7	4.4
Gestational diabetes	77.4	1.9	8.4	5.3	2.7	4.4
Asthma	84.4	0.9	1.8	3.4	3.8	5.7
Depression	87.2	0.7	1.8	2.7	2.8	4.8
Substance use	88.5	0.7	1.7	2.5	2.5	4.1
Preexisting diabetes	92.0	0.5	1.1	1.7	1.7	3.0
Autoimmune conditions	72.7	2.7	3.8	5.4	9.3	6.1
Congenital cardiac disease	86.0	1.0	2.3	2.4	3.5	4.8

[1] Abbreviations: HTN: hypertension; PE: preeclampsia

Multivariate Results

The results of multivariable logistic regression analysis are presented in **Table 4.5**. Adjusting for confounders and other chronic conditions, the odds of SMM were 4.08 (95% CI: 3.71-4.48) for deliveries to women with severe preeclampsia, 2.65 (95% CI: 2.23-3.15) for superimposed preeclampsia, 2.30 (95% CI: 2.09-2.53) for mild preeclampsia, 1.60 (95% CI: 1.46-1.75) for gestational hypertension and 1.50 (95% CI: 1.32-1.70) for chronic hypertension compared to deliveries to women without hypertension. Excluding blood transfusion, the adjusted odds of SMM did not change markedly by type of hypertensive disorder; however there were differences in the magnitude of point estimates. When SMM was considered without blood transfusion, odds estimates were either the same or lower for all maternal hypertensive disorders, with the exception of superimposed preeclampsia, which was higher (from 2.65 to 3.34).

Deliveries to women with autoimmune conditions showed the highest odds of SMM (aOR: 1.81; 95% CI: 1.54-2.14) among other chronic conditions (**Table 4.5**). Depression also was associated with increased odds of SMM (aOR 1.24; 95% CI: 1.11-1.38). Pre-existing diabetes, asthma and substance use disorders were associated with slightly increased odds of SMM ($p<0.05$). The odds of SMM were not increased for

gestational diabetes. When transfusion was excluded, the odds of SMM remained significant only for autoimmune conditions, asthma and pre-existing diabetes.

Table 4.5 Unadjusted and Adjusted Odds of Severe Maternal Morbidity at Delivery, Deliveries to MA Women, 2000-2012

	Unadjusted OR of SMM (95% CI)	Adjusted OR of SMM25[1] (95% CI)	Adjusted OR of SMM24[1] (no blood transfusion) (95% CI)
Hypertensive disorders (Reference= None)			
Superimposed PE	**7.04 (6.02-8.22)**	**2.65 (2.23-3.15)**	**3.34 (2.72-4.10)**
Severe preeclampsia	**10.42 (9.66-11.23)**	**4.08 (3.71-4.48)**	**3.96 (3.48-4.50)**
Mild preeclampsia	**3.43 (3.14-3.74)**	**2.30 (2.09-2.53)**	**2.12 (1.84-2.45)**
Chronic hypertension	**2.37 (2.10-2.66)**	**1.50 (1.32-1.70)**	**1.50 (1.26-1.79)**
Gestational hypertension	**1.82 (1.67-1.99)**	**1.60 (1.46-1.75)**	**1.60 (1.40-1.83)**
Other chronic conditions (Reference=None)			
Gestational diabetes	**1.33 (1.23-1.44)**	0.94 (0.86-1.03)	0.98 (0.87-1.11)
Asthma	**1.55 (1.42-1.70)**	**1.12 (1.01-1.23)**	**1.18 (1.02-1.36)**
Depression	**1.67 (1.51-1.84)**	**1.24 (1.11-1.38)**	1.12 (0.95-1.32)
Substance use disorder	**1.74 (1.53-1.99)**	**1.20 (1.03-1.40)**	1.23 (0.97-1.54)
Preexisting diabetes	**2.52 (2.23-2.85)**	**1.17 (1.03-1.34)**	**1.27 (1.07-1.51)**
Autoimmune conditions	**2.61 (2.24-3.04)**	**1.81 (1.54-2.14)**	**2.13 (1.72-2.64)**

[1]Adjusted for: race/ethnicity, education, age, hospital level, parity, plurality, prenatal care, cigarette use, method of delivery, insurance status, year, low birth weight, congenital cardiac conditions
Bold indicates $p<0.05$.

Social and biological characteristics were also associated with increased odds of SMM (**Table 4.6**). Deliveries to women aged greater than thirty-five years had increased odds of SMM compared to deliveries to women aged 25-29 years. Deliveries to Hispanic and non-Hispanic black women also had increased odds of SMM compared to those for non-Hispanic white women. Deliveries to women with a bachelor's degree or greater had decreased odds of SMM compared to those to women with a high school education. Deliveries to women on public insurance had increased odds of SMM at delivery compared to those on private insurance. The odds of SMM were greater among deliveries to women with no prenatal care compared to receipt of care in the first trimester.

Smoking during pregnancy was associated with decreased odds of SMM at delivery. Deliveries to women with higher-order multiples or LBW infants had a greater odds of SMM, while deliveries at lower level hospitals had decreased odds of SMM at delivery.

Table 4.6 Unadjusted and Adjusted Logistic Regression Models of Severe Maternal Morbidity at Delivery, by Social and Biological Characteristics, Deliveries to MA Women 2000-2012

	Unadjusted OR of SMM25 (95% CI)	Adjusted OR of SMM25[1] (95% CI)
Maternal age (years)		
<20	**1.17 (1.07-1.28)**	1.03 (0.93-1.14)
20-24	1.03 (0.97-1.11)	0.96 (0.89-1.03)
25-29	Ref	Ref
30-34	**0.97 (0.92-1.03)**	1.02 (0.96-1.08)
35-39	1.27 (1.19-1.35)	**1.20 (1.12-1.28)**
40+	1.84 (1.19-1.35)	**1.44 (1.31-1.58)**
Race/ethnicity		
Hispanic	**1.48 (1.40-1.56)**	**1.24 (1.17-1.33)**
Non-Hispanic White	Ref	Ref
Non-Hispanic Black	**2.10 (1.98-2.22)**	**1.45 (1.35-1.55)**
Asian/Pacific Islander	**1.26 (1.17-1.36)**	**1.34 (1.24-1.45)**
American Indian/Other	1.10 (0.95-1.28)	0.96 (0.81-1.12)
PNC month initiation		
No PNC	**3.15 (2.54-3.89)**	**1.97 (1.52-2.56)**
1st trimester	Ref	Ref
2nd trimester	**1.12 (1.06-1.19)**	1.05 (0.99-1.11)
3rd trimester	**1.13 (1.00-1.27)**	1.04 (0.92-1.17)
Parity		
1	Ref	Ref
2	**0.76 (0.83-0.80)**	**0.78 (0.73-0.83)**
3+	**1.08 (1.03-1.13)**	0.97 (0.91-1.04)
Plurality		
Singleton	Ref	Ref
Twins	**4.22 (3.92-4.53)**	**1.76 (1.61-1.94)**
Triplets +	**8.08 (6.09-10.72)**	**2.05 (1.53-2.79)**
Education		
<High School	**1.18 (1.11-1.26)**	**1.09 (1.01-1.17)**
High School /GED	Ref	Ref
Some college	1.03 (0.96-1.10)	0.96 (0.90-1.03)
Bachelors +	**0.83 (0.79-0.87)**	**0.88 (0.83-0.93)**
Cigarette Use		
No	Ref	Ref
Yes	**0.84 (0.78-0.91)**	**0.80 (0.73-0.88)**
Hospital Level		
Level 1	**0.61 (0.58-0.65)**	**0.86 (0.81-0.92)**
Level 2	**0.54 (0.51-0.56)**	**0.68 (0.65-0.72)**
Level 3	Ref	Ref
Method of Delivery		
Vaginal	Ref	Ref
VBAC	**1.73 (1.50-1.98)**	**1.83 (1.58-2.11)**

Primary C-section	**4.09 (3.91-4.29)**	**3.08 (2.92-3.26)**
Repeat C-section	**3.13 (2.96-3.30)**	**3.08 (2.90-3.28)**
Insurance Delivery Payer		
Private	Ref	Ref
Public	**1.44 (1.38-1.50)**	**1.27 (1.20-1.34)**
Free care	**1.30 (1.08-1.56)**	0.99 (0.81-1.21)
Self-pay	**1.32 (1.10-1.58)**	**0.80 (0.66-0.98)**
Low birth weight delivery		
No	Ref	Ref
Yes	**3.94 (3.75-4.14)**	**1.79 (1.67-1.92)**
Maternal congenital cardiac disease		
No	Ref	Ref
Yes	**3.78 (3.33-4.28)**	**2.67 (2.33-3.04)**

[1] Adjusted model also controls for maternal hypertensive disorders and other chronic conditions of: gestational diabetes, asthma, depression, substance use, preexisting diabetes, autoimmune conditions as reported in **Table 4.5.**
Bold indicates $p<0.05$

Results with Interaction Terms

A priori interaction terms for hypertensive disorders with chronic conditions, advanced maternal age, and non-Hispanic black race were examined. Simple logistic regression models examined the odds of SMM for deliveries to women with only hypertensive disorders, then only the hypothesized interaction group (chronic condition, age and race), and then both together. These analyses revealed some combinations of hypertensive disorders and chronic conditions, race, and age with significantly increased odds of SMM compared to either individual group; they were examined in multivariable regression models (**Table 4.7**). Black race was examined across all types of maternal hypertensive disorders due to a priori assumptions. Two interaction terms were marginally significant in multivariable models, pre-existing diabetes and superimposed preeclampsia ($p=0.061$) and black race and severe preeclampsia ($p=0.095$), but were not included in the final model because they did not reach the established 0.05 threshold for statistical significance.

Table 4.7 Potential Interaction Terms with Maternal Hypertensive Disorders

Maternal hypertensive disorder	Potential Interaction (Chronic Condition, Race, Age)	OR of SMM with maternal hypertensive disorder only without potential interaction term (95% CI)	OR of SMM with potential interaction term only without maternal hypertensive disorder (95% CI)	OR of SMM with both maternal hypertensive disorder and potential interaction term (95% CI)	P-value for inter-action term in final model
Gestational hypertension	Preexisting diabetes	1.52 (1.39-1.67)	1.58 (1.32-1.89)	3.22 (2.09-4.98)	0.294
	Asthma	1.50 (1.37-1.65)	1.29 (1.16-1.43)	2.50 (1.81-3.46)	0.323
	Autoimmune conditions	1.51 (1.39-1.65)	2.01 (1.67-2.42)	4.88 (2.91-8.20)	0.369
	Black race	1.50 (1.36-1.64)	1.44 (1.35-1.54)	2.56 (2.03-3.24)	0.398
	Maternal age≥40	1.49 (1.36-1.64)	1.41 (1.29-1.55)	2.80 (2.10-3.73)	0.513
Chronic hypertension	Preexisting diabetes	1.91 (1.68-2.18)	1.59 (1.33-1.90)	3.31 (2.34-4.68)	0.456
	Autoimmune conditions	1.93 (1.72-2.18)	2.00 (1.66-2.41)	5.40 (3.02-9.66)	0.207
	Black race	1.68 (1.46-1.93)	1.43 (1.34-1.53)	3.72 (3.03-4.57)	0.183
Mild preeclampsia	Black race	2.84 (2.58-3.12)	1.47 (1.38-1.57)	5.06 (4.10-6.40)	0.577
	Maternal age≥40	2.92 (2.67-3.19)	1.44 (1.32-1.58)	4.62 (3.39-6.30)	0.968
Severe preeclampsia	Black race	9.34 (8.61-10.14)	1.54 (1.44-1.65)	12.16 (10.28-14.39)	0.095
Superimposed preeclampsia	Preexisting diabetes	5.37 (4.46-6.47)	1.58 (1.32-1.89)	11.35 (7.77-16.57)	0.061
	Black race	5.59 (4.66-6.71)	1.43 (1.34-1.53)	8.11 (6.07-10.82)	0.253

Model Fit Diagnostics

An exchangeable correlation structure provided the best fit and the most parsimonious final model. Different correlation structures were also hypothesized. Both exchangeable and unstructured correlations were examined with an exchangeable correlation structure, providing a lower QIC score and more parsimonious model, with no changes in associations. The exchangeable working correlation in the final model was 0.0297, with a minimum cluster size of zero and maximum cluster size of nine.

Quasi-likelihood (QIC) scores also informed model selection, with preference given to lower scores (**Table 4.8**). Marital status, an initial variable for inclusion based on bivariate analyses, was excluded in the final multivariable regression model based on

QIC scores; the model without marital status was more parsimonious and had a lower QIC score. Variance inflation factors were also analyzed in the final model in a linear regression model to assess multicollinearity among variables. Variance inflation for variables ranged from 1.00-1.90, with a mean VIF of 1.19; there was no evidence of multicollinearity.

Table 4.8 Aim 1 Regression Model Correlation Structures and Fit Statistics

	Description	Correlation Structure	QIC
Model 0	HTN only	Exchangeable	106053.8
Model 1	Model 0 + chronic conditions	Exchangeable	105556.8
Model 2	Model 1 + pre-pregnancy conditions	Exchangeable	100748.4
Model 3	Model 2 + delivery conditions	Exchangeable	95093.66
Model 4	Model 3 - marriage	Exchangeable	95092.81
Model 5	Model 4 + interactions	Exchangeable	95103.33
Model 6	Model 5 with unstructured covariance	Unstructured	95092.86

Sensitivity Analyses

Regression models examined SMM both with and without the blood transfusion indicator (**Table 4.5**); no differences were found in the association between maternal hypertensive disorders and SMM, whether SMM was considered with or without blood transfusion. To further understand the association between maternal hypertensive disorders and cardiac-related morbidity, two indicators of cardiac-related SMM, one with shock and one without, were examined (**Table 4.9**). All types of hypertensive disorders, with the exception of gestational hypertension, were associated with increased odds of cardiac-related SMM in both of the models (aOR range: 1.26-1.81).

Table 4.9 Aim 1 Sensitivity Analysis: Multivariable Logistic Regression Models of Cardiac-related Severe Morbidity at Delivery, Deliveries to MA Women 2000-2012

	Adjusted OR of Cardiac-related SMM25 (no shock)[1]	Adjusted OR of Cardiac-related SMM25[1] (with shock)

	(95% CI)	(95% CI)
Hypertensive disorders		
Superimposed PE	**1.68 (1.18-2.39)**	**1.63 (1.16-2.29)**
Severe preeclampsia	**1.81 (1.47-2.23)**	**1.72 (1.40-2.11)**
Mild preeclampsia	**1.26 (1.03-1.55)**	**1.28 (1.05-1.56)**
Chronic hypertension	**1.45 (1.18-1.79)**	**1.38 (1.12-1.70)**
Gestational hypertension	1.13 (0.95-1.35)	1.13 (0.95-1.34)
Other chronic conditions		
Gestational diabetes	1.03 (0.89-1.18)	1.01 (0.88-1.16)
Asthma	1.02 (0.84-1.23)	1.06 (0.89-1.28)
Depression	**1.35 (1.11-1.63)**	**1.30 (1.07-1.57)**
Substance use	0.95 (1 0.69-1.33)	0.92 (0.67-1.27)
Preexisting diabetes	0.79 (0.60-1.04)	0.82 (0.63-1.06)
Autoimmune conditions	**2.04 (1.56-2.67)**	**2.18 (1.69-2.82)**

[1]Adjusted for: race/ethnicity, education, age, hospital level, parity, plurality, prenatal care, cigarette use, method of delivery, insurance status, year, low birth weight, congenital cardiac conditions
Bold indicates statistical significant $p<0.05$

Aim 2 and Aim 3

Dependent Variable: Rehospitalization within 6 weeks and 1 year postpartum

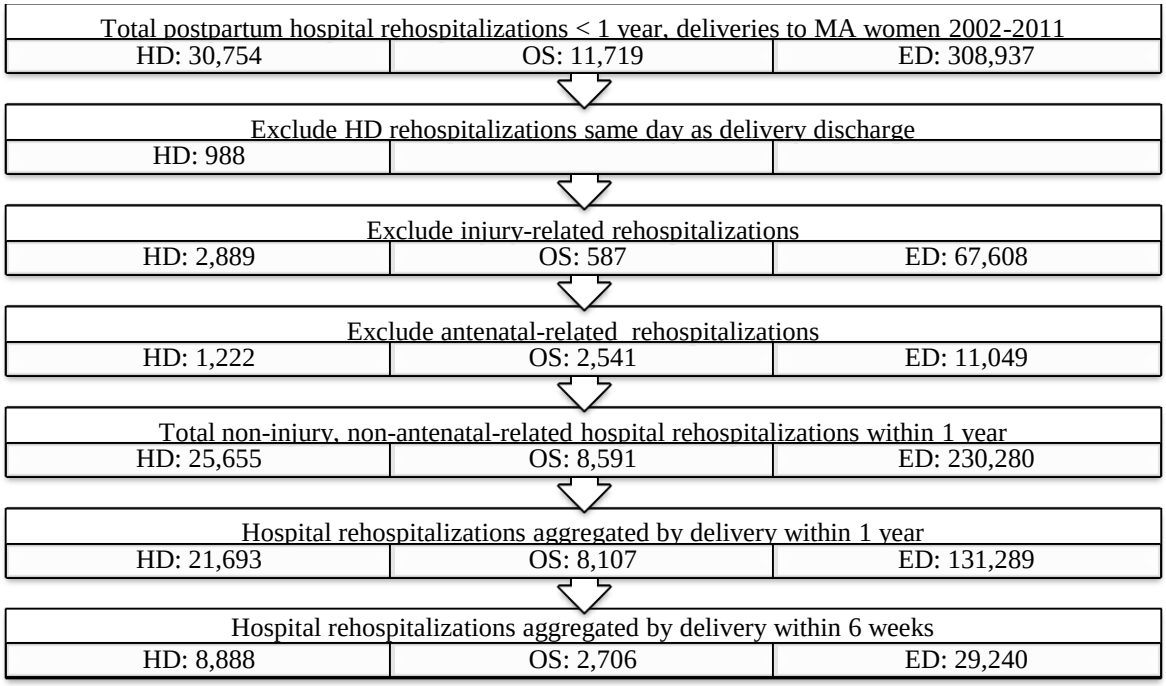
For Aims 2 and 3, the dependent variable was rehospitalization within six weeks and one year postpartum. In Aim 2, the population was restricted to deliveries to women without chronic medical conditions; in Aim 3, all deliveries to women were considered. Before the Aim 2 analyses are presented, an overview is given of the dependent variable for the entire population of deliveries to women in Massachusetts from 2002-2011.

Deliveries to Women in MA, 2002-2011

Over the study period, there were 351,410 hospital rehospitalizations within the first year postpartum to deliveries of resident MA women in the study population. Of these rehospitalizations, 75.2% (n=264,526) were non-injury non-antenatal hospital rehospitalizations within one year postpartum. The proportion of all non-injury-related and non-pregnancy-related rehospitalizations varied by type of rehospitalization: 83.4% for hospital discharge (HD), 74.5% for emergency department (ED), and 73.3% for observational stay (OS) records. **Figure 4.6** shows the step-wise application of exclusion

criteria for each type of rehospitalization record within one year postpartum and the final aggregation of rehospitalizations by delivery for the entire study population.

Figure 4.6 Hospital Rehospitalization Selection and Exclusion Criteria, Deliveries to MA Women 2002-2011

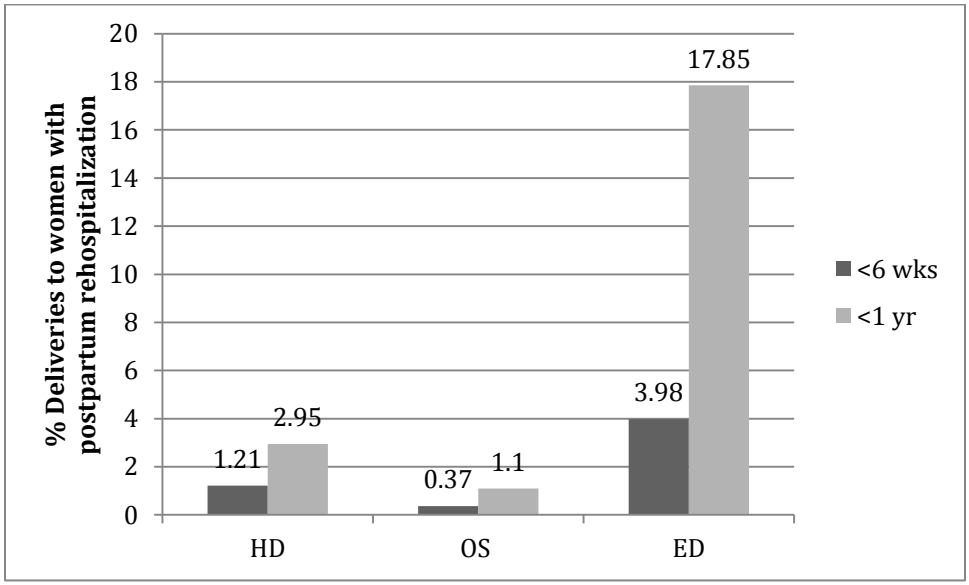


After applying the exclusion criteria, the majority of all hospital rehospitalizations were ED admissions (87.1%) compared to HD (9.7%) and OS rehospitalizations (3.2%). For the first six weeks postpartum, the majority was still from the ED (73.9%) but there was a greater proportion of both HD (20.2%) and OS rehospitalizations (5.9%).

Types of rehospitalizations were then aggregated by delivery; 5.2% of all deliveries to women had at least one hospital rehospitalization (ED, OS, or HD) within the first six weeks postpartum and 19.9% within the first year. Stratifying by rehospitalization types within the first six weeks postpartum, 1.2% of all deliveries to women in the study had at least one HD rehospitalization, 0.4% had at least one OS rehospitalization and 4.0% had at least one ED admission. During the first year

postpartum, 3.0% of all had at least one HD rehospitalization, 1.1%, at least one OS rehospitalization, and 17.9% had at least one ED admission (**Figure 4.7**).

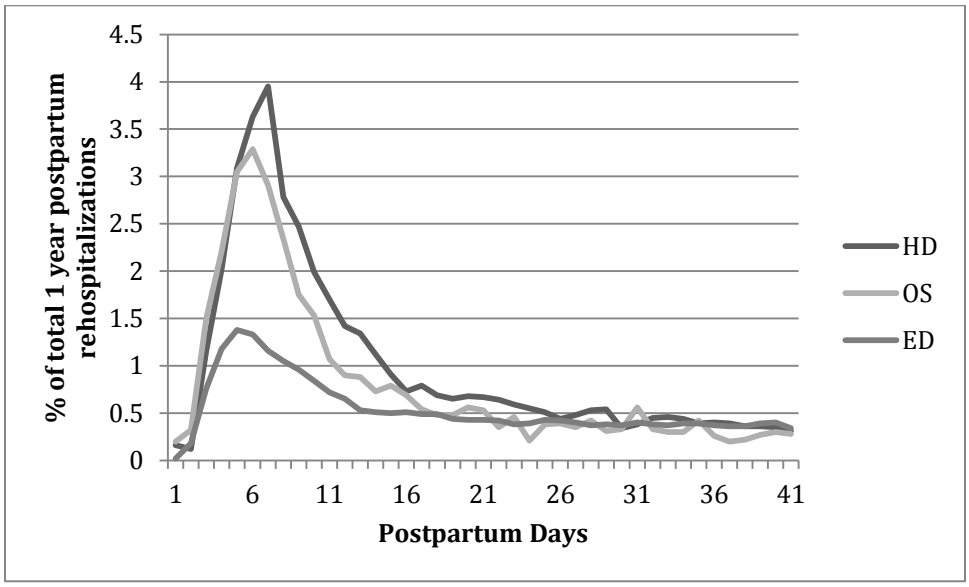
Figure 4.7 Postpartum Rehospitalization by Type and Timing, Deliveries to MA Women 2002-2011



HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

In the first six-week postpartum period, 5.2% of deliveries to women in the study period had at least one rehospitalization; this percentage rose from 4.6% for deliveries in 2002 to 5.5% in 2011 ($p<0.0001$ for trend). More than one quarter (26.1%) of all postpartum rehospitalizations occurred within 42 days postpartum, but this figure varied by type of rehospitalization. Across the first year postpartum, 41.0% of all HD rehospitalizations, 33.4% of all OS rehospitalizations, and 22.3% of all ED admissions occurred in the first six weeks postpartum (**Figure 4.8**). For HD rehospitalizations within the first year, 10.2% occurred within the first seven days postpartum and for OS rehospitalizations, 10.6% were within the first seven days; the figure was 4.9% for ED admissions.

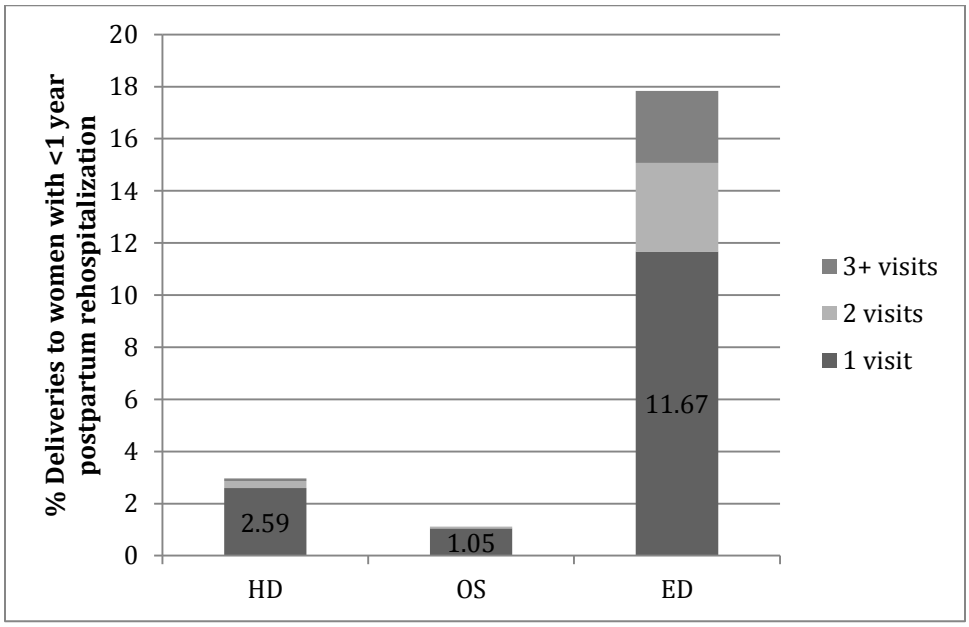
Figure 4.8 Percent of First Year Postpartum Hospital Rehospitalizations by Postpartum Days, Deliveries to MA Women 2002-2012



HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Of all deliveries to women with at least one rehospitalization within the first year postpartum, the majority (63.6%) had only one rehospitalization, 19.5% had two rehospitalizations and 16.9% had three or more rehospitalizations. Stratified by type, the majority of deliveries with HD, OS or ED records had only one rehospitalization, although there was a greater percentage of repeat ED visits than for either HD or OS rehospitalization (**Figure 4.9**).

Figure 4.9 Percent Deliveries with Postpartum Hospital Rehospitalizations within One Year by Type and Frequency, Deliveries to MA Women 2002-2011



HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Over the study period, the percentage of women with any type of hospital rehospitalization in the first year postpartum rose from 18.0% in 2002 to 20.3% in 2011 ($p<0.0001$ for trend). ED admissions rose over the time period from 15.9% to 18.4% ($p<0.0001$). HD rehospitalizations also rose from 2.87 to 3.02% ($p<0.001$), while OS rehospitalizations showed little change. Similar trends were seen in the first six weeks; the percentage ED admissions and HD rehospitalizations increased over the study period ($p<0.0001$ and $p=0.0002$, respectively); no trends were identified with OS rehospitalizations.

The five most common primary diagnoses for rehospitalization varied both by timing (<6 weeks vs. <1 year) and type (ED, OS, HD) (**Table 4.10 & Table 4.11**). Non-specific codes were common across all types of rehospitalization. Among specific codes listed in the primary diagnosis field of the hospitalization record, hypertension was a

common diagnosis for both OS and HD records at both 6 weeks and within 1 year. Postpartum hemorrhage also was a common cause for all types of first rehospitalizations in the first 6 weeks postpartum.

Table 4.10 Top Primary Diagnoses Among Postpartum Women with Hospital Discharge, Observational Stay, and Emergency Department Records within Six Weeks, Deliveries to MA Women 2002-2011

	Hospital Discharge Record		Observational Stay Record		Emergency Department	
Rank	% women with HD record <6 weeks	Primary Diagnosis (ICD-9-CM code)	% women with OS record <6 weeks	Primary Diagnosis (ICD-9-CM code)	% women with ED record <6 weeks	Primary Diagnosis (ICD-9-CM code)
1	20.4	Other and unspecified complications of the puerperium not elsewhere classified	19.3	Hypertension complicating pregnancy childbirth and the puerperium	9.8	Other and unspecified complications of the puerperium not elsewhere classified
2	16.3	Hypertension complicating pregnancy childbirth and the puerperium	14.9	Other and unspecified complications of the puerperium not elsewhere classified	7.9	Other symptoms involving abdomen and pelvis
3	13.9	Major puerperal infection	11.9	Postpartum hemorrhage	5.3	Other current conditions in the mother classifiable elsewhere but complicating pregnancy childbirth or the puerperium
4	8.0	Other current conditions in the mother classifiable elsewhere but complicating pregnancy childbirth or the puerperium	10.6	Other current conditions in the mother classifiable elsewhere but complicating pregnancy childbirth or the puerperium	4.3	Postpartum hemorrhage
5	6.8	Postpartum hemorrhage	4.8	Other complications of pregnancy not elsewhere classified	4.0	Other complications of pregnancy not elsewhere classified

HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Table 4.11 Top Primary Diagnoses Among Postpartum Women with Hospital Discharge and Observational Stay Records within One Year, MA Women with Deliveries 2002-2011

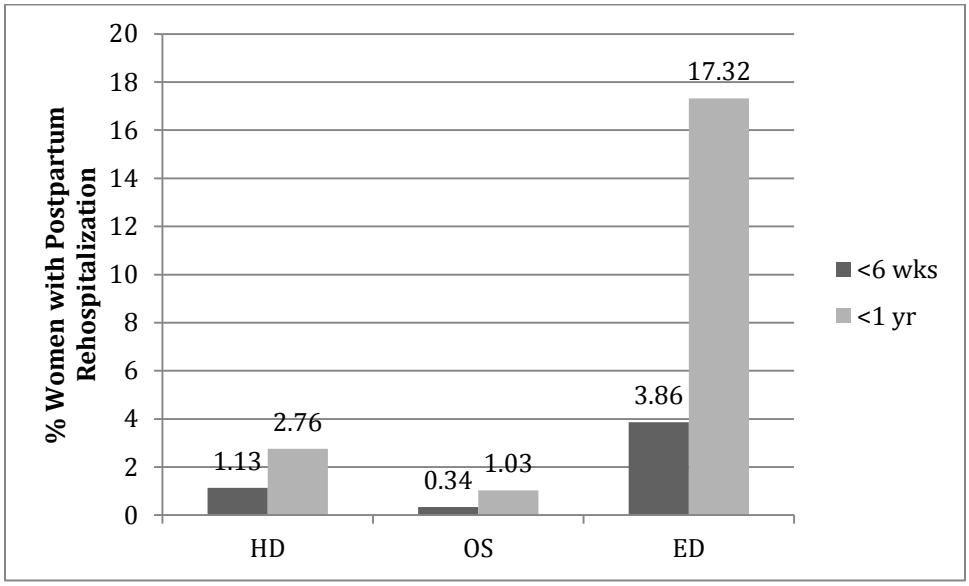
	Hospital Discharge Record		Observational Stay Record		Emergency Department	
Rank	% women with HD record <1 year	Primary Diagnosis (ICD-9-CM code)	% women with ED record <1 year	Primary Diagnosis (ICD-9-CM code)	% women with ED record <1 year	Primary Diagnosis (ICD-9-CM code)
1	9.5	Cholelithiasis	9.7	Cholelithiasis	9.5	Other symptoms involving abdomen and pelvis
2	9.0	Other and unspecified complications of the puerperium not elsewhere classified	6.5	Hypertension complicating pregnancy childbirth and the puerperium	4.4	Symptoms involving respiratory system and other chest symptoms
3	6.7	Hypertension complicating pregnancy childbirth and the puerperium	6.4	Other symptoms involving abdomen and pelvis	3.7	Acute pharyngitis
4	5.8	Major puerperal infection	5.4	Other and unspecified complications of the puerperium not elsewhere classified	3.7	Symptoms involving head and neck
5	4.1	Episodic mood disorders	4.9	Symptoms involving respiratory system and other chest symptoms	3.5	General symptoms

HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Deliveries to Women without Chronic Medical Conditions in MA, 2002-2011

When limited to women without chronic conditions, rehospitalizations patterns were similar to those for the entire population but the rates were attenuated: 1.1% of deliveries to women had HD rehospitalizations within six weeks and 2.8% within one year; 0.3% had OS rehospitalizations within six weeks and 1.0% within one year; and 3.9% had ED admissions within six weeks and 17.3% within one year (**Figure 4.10**).

Figure 4.10 Percent Postpartum Hospital Rehospitalization by Type and Timing, Deliveries to MA Women without Chronic Medical Conditions 2002-2011



HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Aim 2

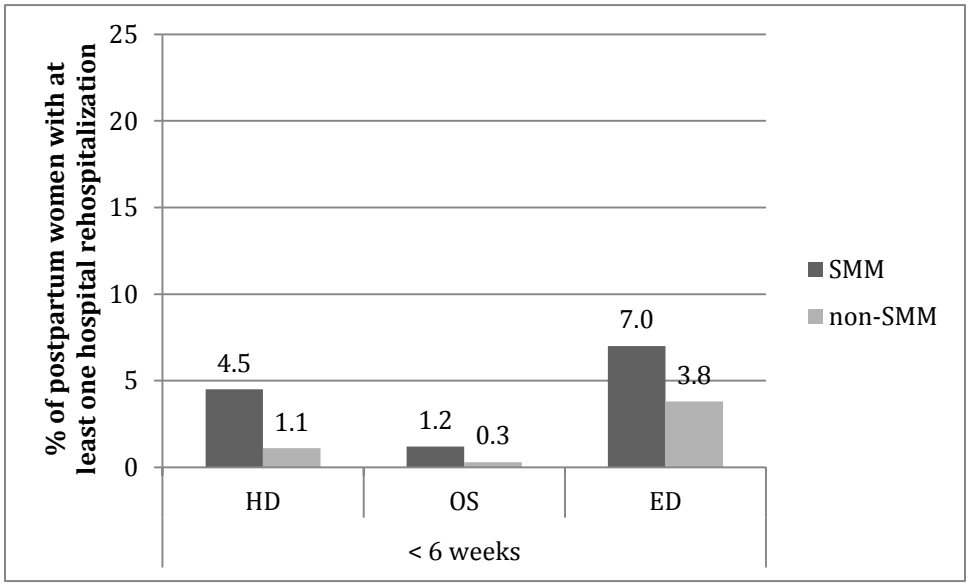
Bivariate Results

Almost three in ten deliveries with SMM (28.3%) to women without chronic medical conditions had at least one rehospitalization within the first year postpartum compared to two in ten (19.2%) without SMM. In the first six weeks postpartum, 11.3% of deliveries to women with SMM at delivery had a rehospitalization compared to 4.9% without SMM. These relations varied by type of rehospitalization (**Figure 4.11** and

Figure 4.12). Among deliveries to women with SMM, 4.5% had an HD rehospitalization within six weeks compared to 1.1% without SMM; within one year, the respective figures were 7.7% and 2.7 %. Within six weeks, 1.2% of deliveries to women with SMM at delivery had an OS rehospitalization compared to 0.3% without and within one year, 2.2% with SMM had at least one OS rehospitalization compared to 1.0% without. Within six weeks, 7.0% of deliveries to women with SMM had an ED admission at six weeks compared to 3.8% without SMM and 23.2% had an ED admission within one year compared to 17.3% without SMM. All bivariate comparisons were significant at $p<0.0001$.

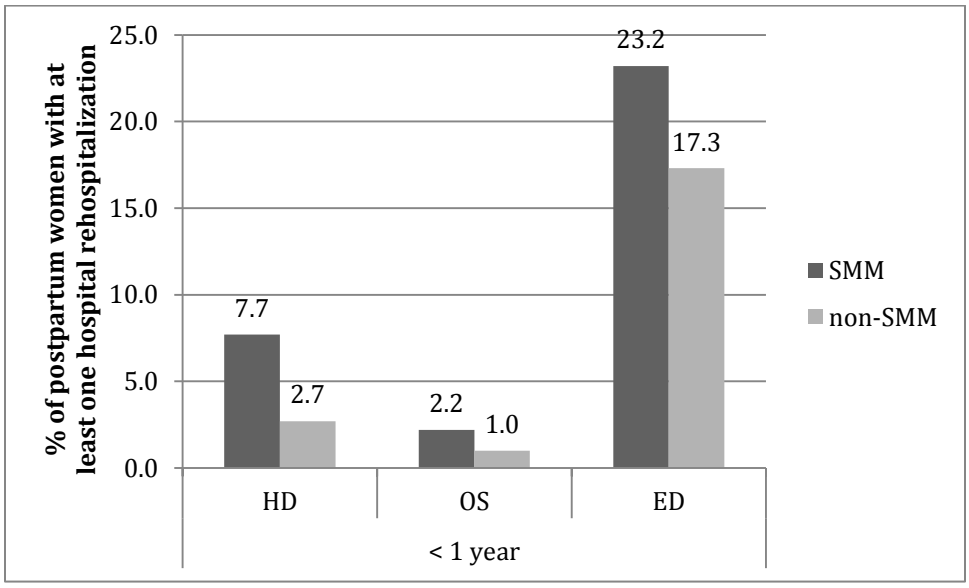
SMM was stratified by specific indicators of severe morbidity and compared by type and timing of hospital rehospitalization (**Table 4.12**). For deliveries to women with renal failure, 6.6% had an HD rehospitalization within the first six weeks and 10.0% within the first year. For deliveries to women with puerperal cerebrovascular disorders, 11.9% had an ED admission within the first six weeks and 34.1% within the first year.

Figure 4.11 Severe Maternal Morbidity at Delivery and Hospital Rehospitalizations within 6 weeks postpartum, Deliveries to MA Women without Chronic Medical Conditions 2002-2012



HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Figure 4.12 Severe Maternal Morbidity at Delivery and Hospital Rehospitalizations within 1 year postpartum, Deliveries to MA Women without Chronic Medical Conditions 2002-2011



HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Table 4.12 Severe Maternal Morbidity Indicators and Hospital Rehospitalizations by Type and Timing, deliveries to MA Women without Chronic Medical Conditions 2002-2012

Classification	HD 6 weeks % (N) (1.13)	OS 6 weeks % (N) (0.34)	ED 6 weeks % (N) (3.86)	HD 1 year % (N) (2.76)	OS 1 year % (N) (1.03)	ED 1 year % (N) (17.32)	Overall SMM at delivery % (N)
1. Acute myocardial infarction	--	--	--	--	--	--	--
2. Acute renal failure	6.64 (14)	--	8.53 (18)	9.95 (21)	--	18.96 (40)	0.03 (211)
3. Adult respiratory distress syndrome	--	--	10.24 (17)	10.24 (17)	--	29.52 (49)	0.02 (166)
4. Amniotic fluid embolism	--	--	--	--	--	--	0.00 (22)
5. Aneurysm	--	--	--	--	--	--	--
6. Cardiac arrest/ventricular fibrillation	--	--	--	--	--	--	0.00 (30)
7. Disseminated intravascular coagulation	4.77 (25)	--	5.34 (28)	6.68 (35)	2.10 (11)	15.65 (82)	0.08 (524)
8. Eclampsia	--	--	10.89 (22)	5.94 (12)	--	28.22 (57)	0.03 (202)
9. Heart failure during procedure or surgery	5.43 (31)	--	8.06 (46)	9.81 (56)	2.63 (15)	23.12 (132)	0.08 (571)
10. Internal injuries of thorax, abdomen, and pelvis	--	--	--	--	--	--	0 (33)
11. Intracranial injuries	--	--	--	--	--	--	--
12. Puerperal cerebrovascular disorders	--	--	11.90 (15)	14.29 (18)	--	34.13 (43)	0.02 (126)
13. Pulmonary edema	--	--	--	--	--	21.88 (14)	0.01 (64)
14. Severe anesthesia complications	--	--	--	--	--	20.75 (11)	0.01 (53)
15. Sepsis	--	--	--	11.27 (16)	--	26.06 (37)	0.02 (142)
16. Shock	--	--	--	9.92 (12)	--	23.14 (28)	0.02 (121)

17. Sickle cell anemia with crisis	--	--	--	27.27 (12)	--	--	0.01 (44)
18. Thrombotic embolism	--	--	--	13.08 (14)	--	31.78 (34)	0.02 (107)
19. Blood transfusion	4.35 (201)	1.21 (56)	7.03 (325)	7.63 (353)	2.18 (101)	23.72 (1097)	0.67 (4625)
20. Cardio monitoring	--	--	--	--	2.13(12)	--	0.00 (34)
21. Conversion of cardiac rhythm	--	--	--	--	--	--	0.00 (22)
22. Hysterectomy	3.70 (17)	--	5.66 (26)	6.32 (29)	--	18.52 (85)	0.07 (459)
23. Operations on heart and pericardium	3.37 (19)	--	4.79 (27)	5.50 (31)	2.13 (12)	19.33 (109)	0.08 (564)
24. Temporary tracheostomy	3.72 (11)	--	--	--	--	--	0.04 (296)
25. Ventilation	3.72 (11)	--	10.14 (30)	8.45 (25)	--	31.08 (92)	0.04 (296)

HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department
-- Suppressed Cell size <11

Other social and biological characteristics were associated with postpartum hospital rehospitalizations, all with significant Wald χ^2 statistical tests ($p<0.0001$) (**Table 4.13**). These characteristics were considered as confounders in the analysis of the relation of SMM with rehospitalization.

Table 4.13 Social and Biological Characteristics and Postpartum Hospital Rehospitalizations by Type and Timing, Deliveries to MA Women without Chronic Medical Conditions 2002-2012

Characteristic (%)	HD 6 weeks 1.13%	HD 1 year 2.76%	OS 6 weeks 0.34%	OS 1 year 1.03%	ED 6 weeks 3.86%	ED 1 year 17.32%	Total, N (N=685,228)
Age							
<20	1.43	3.68	0.40	1.39	7.38	36.42	41,138
20-24	1.25	3.43	0.35	1.22	6.40	30.40	108,760
25-29	1.06	2.69	0.31	0.97	3.99	17.97	116,122
30-34	1.04	2.40	0.33	0.91	2.71	11.63	216,818
35-39	1.12	2.50	0.38	0.98	2.55	10.18	124,066
40+	1.49	3.16	0.41	1.12	2.69	10.38	28,312
Race/ethnicity							
Hispanic	1.27	3.12	0.31	1.10	5.07	23.88	96,025
NH White	1.05	2.68	0.35	1.03	3.66	16.02	465,374
NH Black	1.87	3.81	0.46	1.31	4.88	24.91	56,105
NH Asian	0.87	1.61	0.26	0.54	2.09	7.52	53,078
NH Other	1.23	2.98	0.35	1.05	4.73	22.41	13,614
Education							
<HS	1.23	3.48	0.35	1.20	6.57	29.69	73,430
HS/GED	1.30	3.37	0.36	1.20	5.23	24.14	251,618
Some college	1.15	2.93	0.41	1.20	3.61	16.62	68,007
Bachelors +	0.96	2.00	0.32	0.79	2.03	8.44	290,664
Insurance Payer							
Private	0.99	2.22	0.34	0.92	2.35	10.33	411,556
Public	1.36	3.62	0.35	1.20	6.28	28.53	261,280
Free care	1.22	2.29	0.37	0.90	2.11	10.43	6,776
Self-pay	1.15	3.01	0.21	0.86	3.62	16.57	5,584
Marital Status							
Married	1.04	2.32	0.34	0.91	2.75	11.61	466,875
Not married	1.33	3.69	0.36	1.28	6.23	29.53	218,210
Cigarette use in pregnancy							
Yes	1.40	4.92	0.42	1.56	3.47	37.93	49,551
No	1.11	2.59	0.34	0.98	8.73	15.70	634,555
PNC initiation							
No PNC	1.59	4.41	0.50	1.36	6.41	24.51	2,199
1st trimester	1.11	2.67	0.35	1.03	3.60	16.34	561,014
2nd trimester	1.22	3.15	0.32	1.01	4.96	22.18	95,215
3rd trimester	1.15	3.08	0.30	0.94	5.37	20.56	19,072
Parity							
1	1.25	2.70	0.37	0.97	4.06	17.46	309,709

2	0.98	2.57	0.31	1.01	3.4	16.05	235,409
3+	1.14	3.20	0.35	1.17	4.11	19.19	137,098
Plurality							
Singletons	1.10	2.72	0.34	1.02	3.86	17.40	669,570
Twins	2.45	4.28	0.45	1.33	3.71	14.19	15,168
Triplets +	4.29	5.71	1.63	2.45	3.88	14.29	490
Method of Delivery							
Vaginal	0.93	2.48	0.30	0.96	3.53	17.18	461,001
VBAC	0.99	2.39	0.37	1.01	3.15	14.53	14,499
Primary	1.83	3.51	0.46	1.13	4.3	17.82	124,987
Cesarean	1.27	3.22	0.41	1.22	4.48	17.84	84,077
Repeat Cesarean							
Hospital Level							
1	0.93	2.64	0.36	1.13	5.38	22.90	135,866
2	1.06	2.65	0.31	0.90	4.19	17.59	259,904
3	1.30	2.91	0.36	1.10	2.84	14.46	288,111
Length of Stay at delivery							
1-2 days	0.76	2.23	0.26	0.89	3.39	16.89	197,963
3-4 days	1.23	2.93	0.38	1.08	4.08	17.50	320,531
5+ days	2.33	4.28	0.55	1.36	4.86	18.42	66,734
Low birth weight delivery							
Yes	1.85	4.09	0.42	1.27	4.95	20.78	44,736
No	1.08	2.66	0.34	1.01	3.76	17.05	637,625
Gestational diabetes	1.54	3.48	0.48	1.47	4.31	17.79	34,436
Yes	1.11	2.72	0.34	1.00	3.83	17.30	650,792
No							
Mild/severe preeclampsia							
Yes	3.50	5.76	0.96	1.93	5.64	20.25	7,008
No	1.11	2.73	0.34	1.02	3.84	17.29	678,220
Gestational hypertension							
Yes	2.20	4.06	0.73	1.71	4.42	18.49	25,730
No	1.09	2.71	0.33	1.00	3.83	17.28	659,498

HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department

Confounder Results

Table 4.14 shows the variation in SMM both with and without transfusion by social and biological characteristics as well as other pregnancy-associated conditions. With a population of about 685,000 women without chronic conditions, all Wald χ^2 analyses were significant ($p<0.0001$). Maternal age, education, race/ethnicity, parity, plurality, cigarette use during pregnancy, hospital level, insurance payer, method of

delivery, low birth weight delivery, marital status and all chronic and pregnancy-related chronic conditions were significantly associated with SMM both with and without transfusion.

Table 4.14 Sample Characteristics by Severe Maternal Morbidity at Delivery, Deliveries to MA Women without Chronic Medical Conditions 2002-2011

Characteristic	SMM without transfusion Rate per 10,000 deliveries; 43 (N=2913)	SMM with transfusion Rate per 10,000 deliveries; 99 (N=6746)	Total, N (N=685,228)
Age			
<20	36 (148)	112 (459)	41,138
20-24	31 (337)	94 (1027)	108,760
25-29	37 (607)	91 (1504)	116,122
30-34	40 (857)	88 (1917)	216,818
35-39	58 (718)	114 (1420)	124,066
40+	87 (246)	160 (453)	28,312
Race/ethnicity			
Hispanic	47 (449)	123 (1179)	96,025
Non-Hispanic White	37 (1702)	84 (3931)	465,374
Non-Hispanic Black	80 (448)	168 (943)	56,105
Non-Hispanic Asian	44 (231)	106 (561)	53,078
Other	48 (66)	98 (134)	13,614
Education			
<HS	39 (289)	122 (897)	73,430
HS/GED	45 (1134)	104 (2624)	251,618
Some college	47 (318)	105 (711)	68,007
Bachelors +	39 (1146)	86 (2495)	290,664
Insurance Payer			
Private	40 (1635)	86 (3537)	411,556
Public	46 (1199)	118 (3095)	261,280
Free care	78 (53)	128 (87)	6,776
Self-pay	47 (26)	109 (61)	5,584
Marital Status			
Married	41 (1937)	92 (4274)	466,875
Not married	44 (967)	114 (2492)	218,210
Cigarette use in pregnancy			
Yes	29 (2749)	83 (412)	49,551
No	43 (145)	100 (6334)	634,555
PNC month initiation			
No PNC	123 (27)	282 (62)	2,199
1st trimester	42 (2354)	95 (5326)	561,014
2nd trimester	41 (389)	106 (1012)	95,215
3rd trimester	39 (74)	106 (202)	19,072
Parity			
1	43 (1331)	103 (3289)	309,709
2	35 (823)	80 (1884)	235,409
3+	53 (723)	113 (1548)	137,098
Plurality			

Singletons	39 (2627)	91 (6123)	669,570
Twins	173 (262)	409 (620)	15,168
Triplets +	82 (24)	755 (37)	490
Method of Delivery			
Vaginal	20 (903)	56 (2596)	461,001
VBAC	46 (66)	104 (151)	14,499
Primary Cesarean	99 (1234)	213 (2668)	124,987
Repeat Cesarean	84 (703)	161 (1353)	84,077
Hospital Level			
1	26 (359)	82 (1114)	135,866
2	31 (800)	73 (1905)	259,904
3	61 (1748)	129 (3725	288,111
Length of Stay at delivery			
1-2 days	5 (137)	20 (589)	297,963
3-4 days	58 (912)	90 (2890)	320,531
5+ days	279 (1864)	495 (3301)	66,734
Low birth weight delivery			
Yes	165 (736)	310 (1387)	44,736
No	33 (2097)	82 (5250)	637,625
Gestational diabetes			
Yes	60 (208)	126 (435)	34,436
No	42 (2705)	97 (6345)	650,792
Mild/severe preeclampsia			
Yes	432 (303)	796 (558)	7,008
No	38 (2610)	92 (6222)	678,220
Gestational hypertension			
Yes	59 (153)	139 (357)	25,730
No	42 (2760)	97 (6423)	659,498

Main Multivariate Results

Multivariable regression results are presented below for SMM with and without transfusion across HD (**Table 4.15**), OS (**Table 4.16**), and ED visits (**Table 4.17**). There was increased risk of HD rehospitalization among deliveries to women with SMM compared to those without SMM within six weeks (aRR 2.48; 95% CI: 2.20-2.80) and one year postpartum (aRR: 2.04; 95% CI: 1.87-2.23) (**Table 4.15)** after adjustment for confounders. The adjusted relative risk of HD rehospitalization at 42-364 days postpartum was markedly less than the risk within six weeks (aRR: 1.65; 95% CI: 1.44-1.89 vs. aRR 2.48; 95% CI: 2.20-2.80).

SMM was also associated with an increased risk of OS rehospitalization within six weeks (aRR 2.47; 95% CI: 1.94-3.14) (**Table 4.16**). There also appeared to be an

increased risk within one year (aRR 1.69; 95% CI: 1.43-2.01); however, there was no significant increased risk of OS rehospitalization between 42-364 days for deliveries to women with SMM at delivery (aRR: 1.26; 95% CI: 0.99-1.61) after adjustment of confounders.

For ED admissions within six weeks, women with SMM at delivery had an almost 50% increased risk compared to women without SMM at delivery, after adjustment for confounders (aRR: 1.47; 95% CI: 1.34-1.61) (**Table 4.17)**. Within one year, there was still an increased risk of ED admissions among deliveries to women who experienced SMM at delivery compared to those without (aRR: 1.16; 95% CI: 1.11-1.21), but the risk was attenuated from the estimate seen within six weeks. The risk associated with deliveries of women with SMM was slightly increased (aRR: 1.08; 95% CI: 1.03-1.14) when ED readmission was examined between 42-364 days.

Across all outcomes and time points, adjusted risk estimates for rehospitalization were similar when SMM was defined with and without transfusion; however, there were slight differences in the magnitude of some estimates. Compared to SMM without transfusion, risk point estimates were higher for SMM with transfusion for six-week HD (2.48 vs. 2.27) and OS (2.47 vs. 2.10) rehospitalization.

Table 4.15 Relative Risk of Postpartum Hospital Discharges by Timing, Deliveries to MA Women without chronic medical conditions 2002-2011

	<42 days Postpartum Rehospitalization		42-<365 days Postpartum Rehospitalization		<365 days Postpartum Rehospitalization	
	RR HD (95% CI)	aRR[1] HD (95% CI)	RR HD (95% CI)	aRR[1] HD (95% CI)	RR HD (95% CI)	aRR[1] HD (95% CI)
SMM: no transfusion	4.27 (3.62-5.03)	2.27 (1.91-2.70)	2.08 (1.71-2.53)	1.66 (1.35-2.03)	2.97 (2.63-3.36)	1.96 (2.63-3.36)
SMM: with transfusion	4.12 (3.68-4.60)	2.48 (2.20-2.80)	1.99 (1.74-2.27)	1.65 (1.44-1.89)	2.85 (2.62-3.10)	2.04 (1.87-2.23)

[1]Adjusted for: age, race/ethnicity, pregnancy-related conditions (preeclampsia, gestational hypertension, gestational diabetes), education, method of delivery, insurance status, parity, plurality, length of stay at delivery hospitalization, year, hospital level, marital status, smoking status

Table 4.16 Relative Risk of Postpartum Observation Stays by Timing, Deliveries to MA Women without chronic medical conditions 2002-2011

	<42 days Postpartum Rehospitalization		42-<365 days Postpartum Rehospitalization		<365 days Postpartum Rehospitalization	
	RR OS (95% CI)	aRR[1] OS (95% CI)	RR OS (95% CI)	aRR[1] OS (95% CI)	RR OS (95% CI)	aRR[1] OS (95% CI)
SMM: no transfusion	3.12 (2.19-4.44)	2.10 (1.46-3.03)	1.56 (1.10-2.22)	1.25 (0.87-1.81)	2.08 (1.63-2.67)	1.57 (1.21-2.03)
SMM: with transfusion	3.47 (2.77-4.33)	2.47 (1.94-3.14)	1.52 (1.20-1.92)	1.26 (0.99-1.61)	2.16 (1.84-2.54)	1.69 (1.4-2.01)

[1]Adjusted for: age, race/ethnicity, pregnancy-related conditions (preeclampsia, gestational hypertension, gestational diabetes), education, method of delivery, insurance status, parity, plurality, length of stay at delivery hospitalization, year, hospital level, marital status, smoking status

Table 4.17 Relative Risk of Postpartum Emergency Department Visits by Timing, Deliveries to MA Women without chronic medical conditions 2002-2011

	<42 days Postpartum Rehospitalization		42-<365 days Postpartum Rehospitalization		<365 days Postpartum Rehospitalization	
	RR ED (95% CI)	aRR[1] ED (95% CI)	RR ED (95% CI)	aRR[1] ED (95% CI)	RR ED (95% CI)	aRR[1] ED (95% CI)
SMM: no transfusion	1.80 (1.57-2.05)	1.49 (1.30-1.71)	1.13 (1.03-1.23)	1.09 (0.99-1.18)	1.28 (1.19-1.37)	1.17 (1.09-1.25)
SMM: with transfusion	1.83 (1.67-2.00)	1.47 (1.34-1.61)	1.21 (1.14-1.28)	1.08 (1.03-1.14)	1.35 (1.29-1.41)	1.16 (1.11-1.21)

[1]Adjusted for: age, race/ethnicity, pregnancy-related conditions (preeclampsia, gestational hypertension, gestational diabetes), education, method of delivery, insurance status, parity, plurality, length of stay at delivery hospitalization, year, hospital level, marital status, smoking status

Table 4.18 and **Table 4.19** show the risk of rehospitalization across the different types of hospital encounters by all other variables in the fully adjusted model. There were qualitatively different findings across the types of encounters. For example, deliveries among older women had an increased risk of HD and OS rehospitalization but a decreased risk of ED admission at six weeks and one year. Deliveries to non-Hispanic black women had higher risk of HD and OS rehospitalization compared to white women but no difference in risk of ED admission within six weeks. The risk of ED admission was greater for deliveries paid for by public insurance than for HD rehospitalization. Lower level of hospital at delivery was associated with an increased risk of ED admission but a decreased risk of HD rehospitalization.

Table 4.18 Adjusted Relative Risk of 6 week Rehospitalizations by Social and Biological Characteristics, Deliveries to MA Women 2002-2011

Characteristic	aRR Hospital Discharge Rehospitalization[1] (95% CI)	aRR Observational Stay Rehospitalization[1] (95% CI)	aRR Emergency Department Rehospitalization[1] (95% CI)
Age			
<20	**1.18 (1.06-1.31)**	**1.26 (1.03-1.54)**	**1.28 (1.22-1.34)**
20-24	1.06 (0.98-1.14)	1.13 (0.98-1.31)	**1.18 (1.14-1.22)**
25-29	REF	REF	REF
30-34	1.06 (0.99-1.13)	1.09 (0.97-1.12)	**0.88 (0.84-0.91)**
35-39	**1.11 (1.03-1.19)**	**1.13 (1.07-1.40)**	**0.83 (0.80-0.87)**
40+	**1.33 (1.19-1.48)**	1.22 (0.99-1.50)	**0.83 (0.77-0.89)**
Race/ethnicity			
Hispanic	**1.10 (1.02-1.18)**	0.91 (0.79-1.05)	**0.90 (0.87-0.93)**
Non-Hispanic White	REF	REF	REF
Non-Hispanic Black	**1.44 (1.34-1.56)**	**1.22 (1.06-1.41)**	1.02 (0.98-1.06)
Non-Hispanic Asian	**0.85 (0.77-0.93)**	**0.80 (0.67-0.96)**	**0.67 (0.63-0.71)**
Other	1.05 (0.90-1.22)	0.97 (0.72-1.31)	0.97 (0.90-1.05)
Education			
<HS	**0.89 (0.82-0.96)**	1.03 (0.89-1.20)	1.03 (0.99-1.07)
HS/GED	REF	REF	REF
Some college	0.92 (0.85-1.00)	1.13 (0.98-1.30)	**0.89 (0.85-0.93)**
Bachelors +	**0.85 (0.79-0.90)**	**0.89 (0.79-0.998)**	**0.70 (0.67-0.72)**
Insurance Payer			
Private	REF	REF	REF
Public	**1.23 (1.16-1.32)**	0.96 (0.86-1.08)	**1.66 (1.61-1.72)**
Self-care	1.12 (0.90-1.40)	1.06 (0.72-1.58)	0.96 (0.81-1.13)
Free care	1.05 (0.82-1.35)	**0.55 (0.30-0.99)**	**1.24 (1.08-1.42)**
Marital Status			

Married	0.98 (0.92-1.05)	1.02 (0.91-1.16)	**0.89 (0.86-0.92)**
Not married	REF	REF	REF
Cigarette use in pregnancy			
Yes	**1.25 (1.15-1.36)**	**1.24 (1.06-1.45)**	**1.51 (1.46-1.57)**
No	REF	REF	REF
Parity			
1	REF	REF	REF
2	**0.92 (0.87-0.98)**	0.91 (0.82-1.02)	0.97 (0.94-1.00)
3+	0.98 (0.91-1.05)	0.97 (0.85-1.10)	1.06 (1.02-1.10)
Plurality			
Singletons	REF	REF	REF
Twins	**1.55 (1.30-1.73)**	1.00 (0.78-1.28)	1.05 (0.97-1.13)
Triplets +	**2.11 (1.38-3.22)**	**2.98 (1.48-6.00)**	1.37 (0.88-2.15)
Method of Delivery			
Vaginal	REF	REF	REF
VBAC	1.08 (0.91-1.28)	1.22 (0.92-1.62)	1.05 (0.96-1.15)
Primary Cesarean	**1.28 (1.20-1.37)**	1.08 (0.95-1.23)	**1.24 (1.19-1.28)**
Repeat Cesarean	**1.10 (1.01-1.19)**	1.13 (0.98-1.30)	**1.30 (1.24-1.35)**
Hospital Level			
1	**0.79 (0.74-0.84)**	1.08 (0.97-1.21)	**1.56 (1.51-1.61)**
2	**0.90 (0.85-0.94)**	0.93 (0.85-1.03)	**1.42 (1.38-1.46)**
3	REF	REF	REF
Length of Stay at delivery			
1-2 days	REF	REF	REF
3-4 days	**1.42 (1.33-1.51)**	**1.35 (1.21-1.50)**	**1.18 (1.14-1.21)**
5+ days	**1.95 (1.78-2.14)**	**1.60 (1.35-1.90)**	**1.36 (1.29-1.43)**
Gestational diabetes			
Yes	**1.23 (1.12-1.34)**	**1.33 (1.13-1.56)**	**1.15 (1.09-1.21)**
No	REF	REF	REF
Mild/severe preeclampsia			
Yes	**1.69 (1.48-1.94)**	**2.01 (1.54-2.60)**	**1.26 (1.14-1.39)**
No	REF	REF	REF
Gestational hypertension			
Yes	**1.79 (1.64-1.95)**	**2.03 (1.75-2.37)**	**1.14 (1.08-1.21)**
No	REF	REF	REF

[1]Also adjusted for SMM
Bold indicates p<0.05

Table 4.19 Adjusted Relative Risk of 1 Year Rehospitalizations by Social and Biological Characteristics, Deliveries to MA Women 2002-2011

Characteristic	aRR HD[1] (95% CI)	aRR OS[1] (95% CI)	aRR ED[1] (95% CI)
Age			
<20	**1.14 (1.07-1.22)**	**1.36 (1.22-1.51)**	**1.44 (1.41-1.47)**
20-24	**1.06 (1.01-1.11)**	**1.14 (1.06-1.24)**	**1.24 (1.23-1.26)**
25-29	REF	REF	REF
30-34	1.01 (0.97-1.05)	0.99 (0.92-1.06)	**0.74 (0.71-0.74)**
35-39	1.02 (0.97-1.07)	1.01 (0.94-1.10)	**0.73 (0.71-0.74)**
40+	**1.20 (1.11-1.29)**	1.09 (0.96-1.23)	**0.71 (0.68-0.73)**
Race/ethnicity			
Hispanic	**0.91 (0.86-0.95)**	**0.90 (0.83-0.97)**	**0.89 (0.88-0.91)**
Non-Hispanic White	REF	REF	REF
Non-Hispanic Black	**1.07 (1.02-1.12)**	1.03 (0.95-1.13)	**1.08 (1.07-1.10)**
Non-Hispanic Asian	**0.65 (0.60-0.69)**	**0.57 (0.51-0.64)**	**0.54 (0.52-0.56)**

Other	0.92 (0.83-1.01)	0.89 (0.75-1.06)	1.01 (0.98-1.04)
Education			
<HS	**0.94 (0.90-0.99)**	0.96 (0.88-1.04)	**0.98 (0.97-0.99)**
HS/GED	REF	REF	REF
Some college	0.97 (0.93-1.02)	1.07 (0.99-1.17)	0.92 (0.91-0.94)
Bachelors +	**0.77 (0.74-0.81)**	**0.79 (0.73-0.84)**	**0.67 (0.66-0.68)**
Insurance Payer			
Private	REF	REF	REF
Public	**1.27 (1.22-1.32)**	0.99 (0.93-1.06)	**1.49 (1.46-1.51)**
Self-pay	0.99 (0.84-1.15)	0.96 (0.74-1.23)	1.00 (0.93-1.07)
Free care	**1.20 (1.03-1.40)**	0.81 (0.60-1.08)	**1.21 (1.14-1.29)**
Marital Status			
Married	**0.87 (0.83-0.90)**	**0.87 (0.82-0.93)**	**0.80 (0.79-0.81)**
Not married	REF	REF	REF
Cigarette use in pregnancy			
Yes	**1.52 (1.45-1.59)**	**1.33 (1.23-1.44)**	**1.39 (1.37-1.41)**
No	REF	REF	REF
Parity			
1	REF	REF	REF
2	**1.08 (1.04-1.13)**	**1.16 (1.09-1.23)**	**1.10 (1.09-1.11)**
3+	**1.23 (1.18-1.29)**	**1.27 (1.18-1.37)**	**1.24 (1.22-1.26)**
Plurality			
Singletons	REF	REF	REF
Twins	**1.26 (1.16-1.37)**	1.10 (0.95-1.27)	**0.95 (0.91-0.99)**
Triplets +	**1.46 (1.01-2.10)**	1.71 (0.97-3.01)	1.17 (0.94-1.45)
Method of Delivery			
Vaginal	REF	REF	REF
VBAC	0.93 (0.83-1.03)	0.99 (0.84-1.18)	**0.96 (0.92-0.999)**
Primary Cesarean	**1.12 (1.07-1.17)**	1.00 (0.93-1.08)	**1.06 (1.05-1.08)**
Repeat Cesarean	**1.07 (1.02-1.12)**	1.08 (0.995-1.17)	**1.09 (1.07-1.11)**
Hospital Level			
1	**0.85 (0.81-0.88)**	0.96 (0.90-1.03)	**1.25 (1.23-1.27)**
2	**0.92 (0.89-0.95)**	**0.81 (0.77-0.86)**	**1.15 (1.14-1.16)**
3	REF	REF	REF
Length of Stay at delivery			
1-2 days	REF	REF	REF
3-4 days	**1.28 (1.24-1.33)**	**1.22 (1.15-1.30)**	**1.09 (1.07-1.10)**
5+ days	**1.64 (1.55-1.74)**	**1.45 (1.31-1.61)**	**1.19 (1.16-1.21)**
Gestational diabetes			
Yes	**1.20 (1.13-1.28)**	**1.43 (1.31-1.57)**	**1.12 (1.10-1.15)**
No	REF	REF	REF
Mild/severe preeclampsia			
Yes	**1.44 (1.30-1.59)**	**1.47 (1.23-1.75)**	**1.06 (1.02-1.11)**
No	REF	REF	REF
Gestational hypertension			
Yes	**1.41 (1.33-1.50)**	**1.64 (1.49-1.81)**	**1.09 (1.06-1.12)**
No	REF	REF	REF
Delivery Year			
2002-2003	REF	REF	REF
2004-2005	0.96 (0.92-1.002)	**0.88 (0.82-0.94)**	**1.02 (1.01-1.04)**
2006-2007	0.97 (0.93-1.01)	**0.89 (0.83-0.96)**	**1.10 (1.08-1.12)**
2008-2009	0.98 (0.93-1.02)	**0.87 (0.81-0.94)**	**1.13 (1.11-1.14)**
2010-2011	0.98 (0.94-1.03)	**0.88 (0.82-0.95)**	**1.10 (1.08-1.12)**

[1]Also adjusted for SMM
Bold indicates $p<0.05$

Model Diagnostics

Based on analyses in Aim 1, an exchangeable correlation structure was used to provide the best fit and the most parsimonious final model. The exchangeable working correlation in the final model was 0.0297, with a minimum cluster size of zero and maximum cluster size of nine.

Quasi-likelihood (QIC) scores also informed model selection, with preference given to lower scores. Variance inflation factors were also analyzed in the final model in a linear regression model to assess multicollinearity among variables. Variance inflation for variables ranged from 1.01-1.79, with a mean VIF of 1.28; there was no evidence of multicollinearity.

Sensitivity Analyses

Severe maternal morbidity

SMM is a composite indicator of 25 ICD-9-CM diagnosis and procedure codes and was examined in multiple ways. It was initially analyzed as a dichotomous variable (≥1 SMM indicator vs. 0) and examined both with and without the blood transfusion indicator. There were no differences in adjusted risks across all outcomes when SMM at delivery was considered with or without blood transfusion. In addition, to understand if deliveries to women with multiple SMM indicators had an increased risk of rehospitalization, a sensitivity analysis was performed with categorization of 0, 1, 2+ SMM indicators. In adjusted models, there appeared to be no evidence of increased risk based on number of SMM indicators (**Table 4.20**).

Table 4.20 Aim 2 Sensitivity Analysis: Alternative Categorization of Severe Maternal Morbidity Indicator as Main Independent Variable

	HD 6 wks aRR[1] (95% CI)	HD 1 year aRR[1] (95% CI)	OS 6 wks aRR[1] (95% CI)	OS 1 yr aRR[1] (95% CI)	ED 6 wks aRR[1] (95% CI)	ED 1 yr aRR[1] (95% CI)
No SMM	REF	REF	REF	REF	REF	REF
1 SMM	**2.59 (2.28-2.95)**	**2.03 (1.85-2.24)**	**2.57 (1.99-3.33)**	**1.75 (1.46-2.10)**	**1.48 (1.34-1.63)**	**1.17 (1.11-1.22)**
2+ SMM	**2.29 (1.71-3.08)**	**2.23 (1.82-2.73)**	**2.34 (1.28-4.27)**	1.38 (0.87-2.20)	**1.45 (1.14-1.84)**	**1.19 (1.06-1.33)**

[1]Adjusted for: age, race/ethnicity, pregnancy-related conditions (preeclampsia, gestational hypertension, gestational diabetes), education, method of delivery, insurance status, parity, plurality, length of stay at delivery hospitalization, year, hospital level, marital status, smoking status
Bold indicates $p<0.05$

Mental health indicators

Mental health indicators of substance use disorders and depression were initially not considered in the main multivariable regression model due to null findings from Aim 1 with SMM without transfusion. Sensitivity analyses of adding these mental health indicators in the regression model revealed no difference in the risk of all types of postpartum rehospitalization among deliveries to women with SMM from main the multivariate results. Models of risk of ED admission within one year with the added mental health indicators did not converge with log-binomial regression and were then assessed through a Poisson distribution. Additional assessments of potential interaction between mental health and SMM at delivery were not statistically significant. In adjusted models, risk of rehospitalization across types and time points among deliveries to women with depression ranged from 1.30 to 1.63; deliveries to women with substance use disorders also had an increased risk of rehospitalization ranging from 1.26 to 1.99 across all examined outcomes.

Maternal deaths in the year after delivery

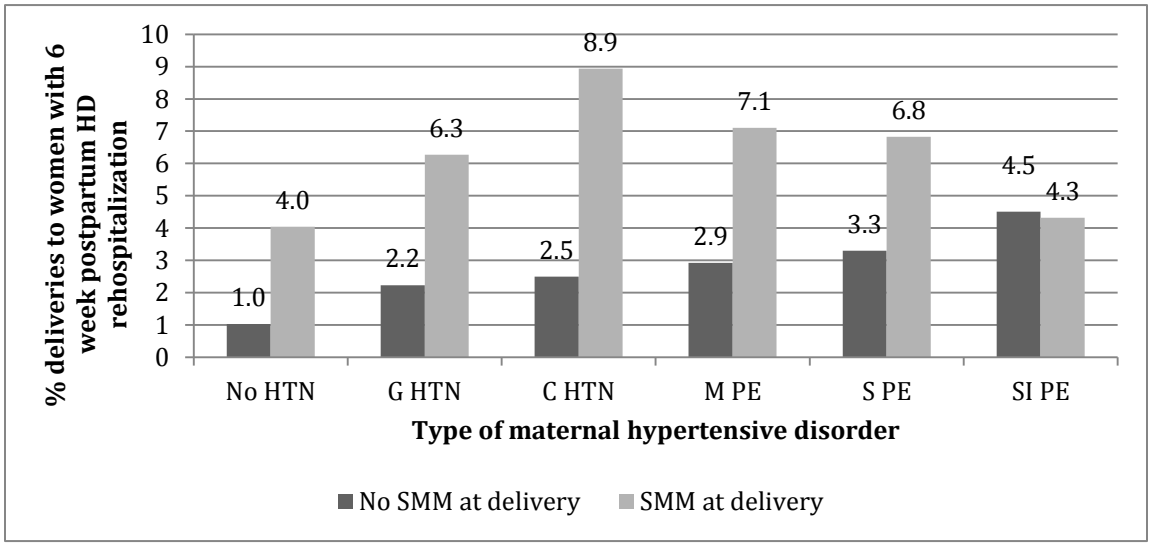
There were 138 maternal deaths after delivery and within the first year postpartum in the delivery population during the study period (0.02%). Thirty-one deaths were within the first six weeks postpartum (22.5%) and 107 were between six and fifty-two weeks (77.5%). Of those who died, 12% had SMM at delivery (N=16) and 11% had either mild or severe preeclampsia or gestational hypertension (N=15). Removing maternal deaths from the study sample did not change the association of SMM at delivery with any type of rehospitalization.

Aim 3

Bivariate Results

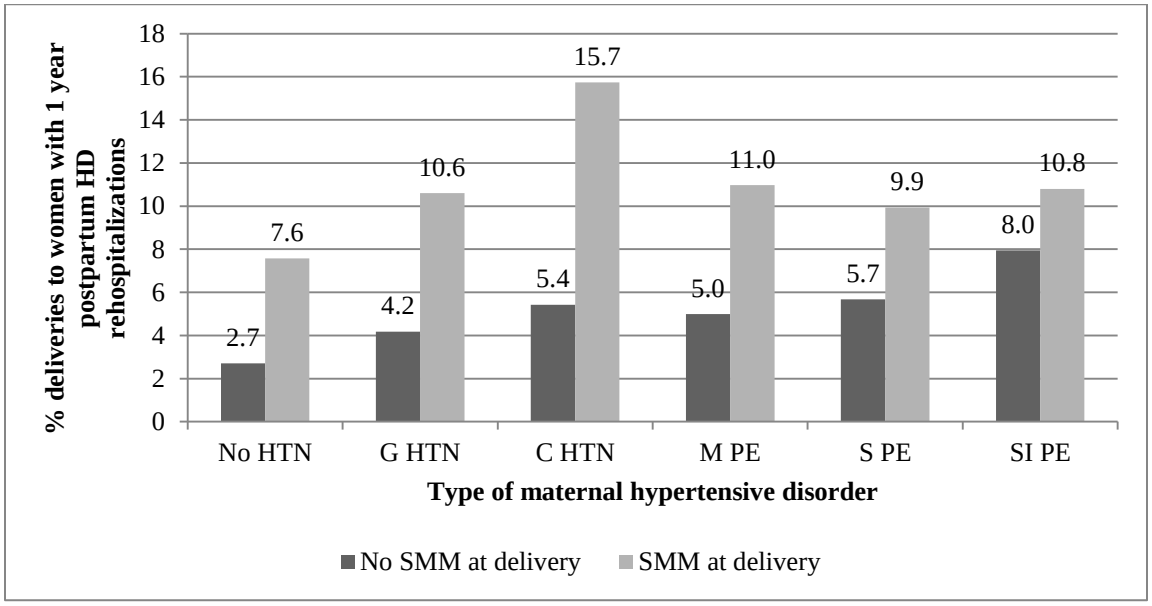
Maternal hypertensive disorder subtypes were stratified by SMM to examine rehospitalization by different types of encounters and timeframes (**Figures 4.13-4.18**). Similar to Aim 1 results, deliveries to women with maternal hypertensive subtypes were more likely to be rehospitalized compared to women without any type of hypertension. Similar to Aim 2 results, deliveries to women with SMM at delivery were more likely to be rehospitalized compared to women without morbidity. In general, the percentage of deliveries with rehospitalization was increased among deliveries with SMM for all subtypes of maternal hypertensive disorders; however, this relation in some instances was not seen for severe or superimposed preeclampsia.

Figure 4.13 Six Week Postpartum Hospital Discharge Rehospitalization by Hypertensive Status and Severe Maternal Morbidity, Deliveries to MA Women 2002-2011



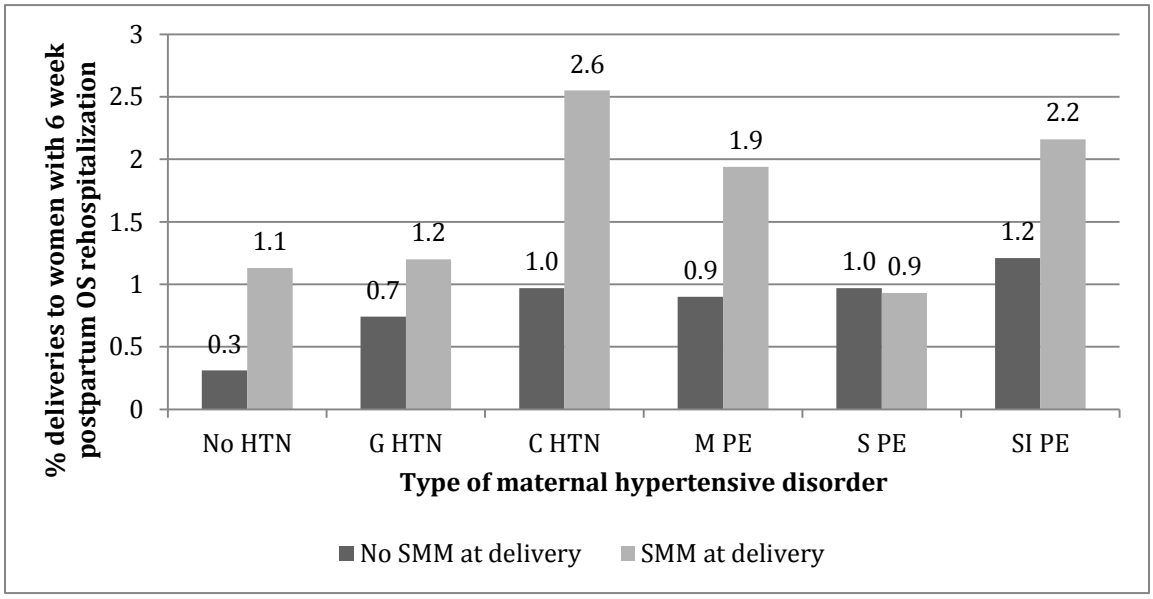
G HTN: Gestational hypertension; C HTN: Chronic hypertension; M PE: Mild preeclampsia; S PE: Severe preeclampsia; SI PE: Superimposed preeclampsia

Figure 4.14 One Year Postpartum Hospital Discharge Rehospitalization by Hypertensive Status and Severe Maternal Morbidity, Deliveries to MA Women 2002-2011



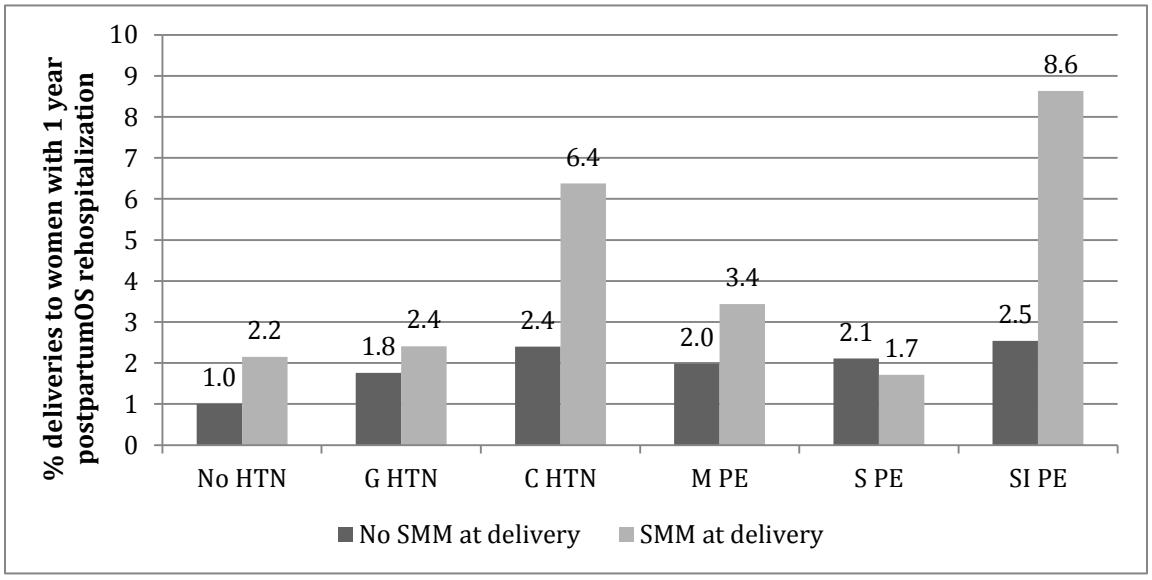
G HTN: Gestational hypertension; C HTN: Chronic hypertension; M PE: Mild preeclampsia; S PE: Severe preeclampsia; SI PE: Superimposed preeclampsia

Figure 4.15 Six Week Postpartum Observational Stay Rehospitalization by Hypertensive Status and Severe Maternal Morbidity, Deliveries to MA Women 2002-2011



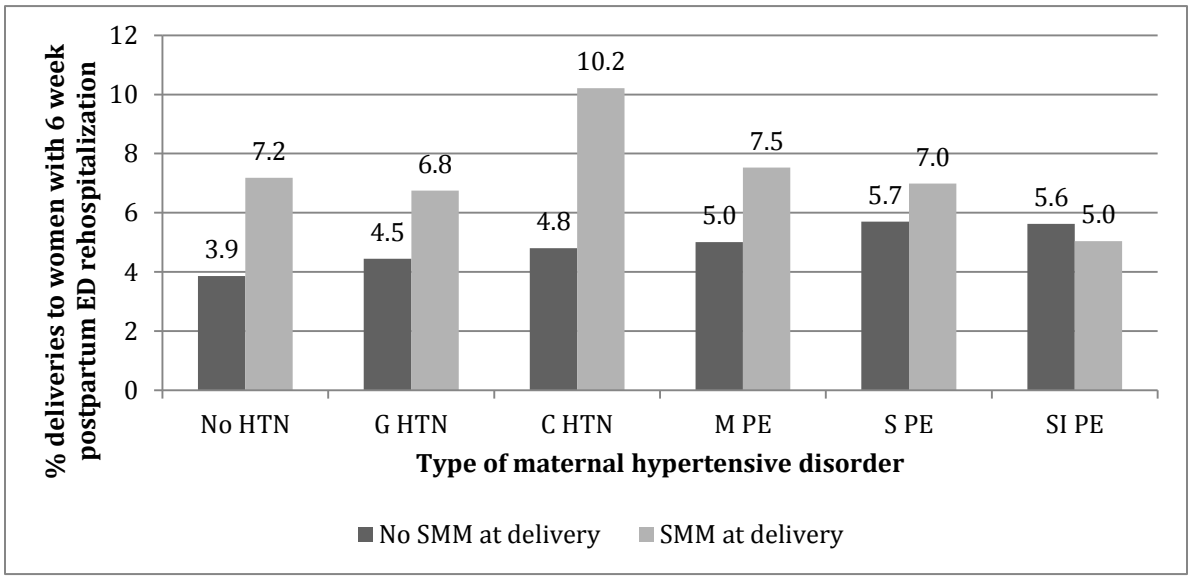
G HTN: Gestational hypertension; C HTN: Chronic hypertension; M PE: Mild preeclampsia; S PE: Severe preeclampsia; SI PE: Superimposed preeclampsia

Figure 4.16 One Year Postpartum Observational Stay Rehospitalization by Hypertensive Status and Severe Maternal Morbidity, Deliveries to MA Women 2002-2011



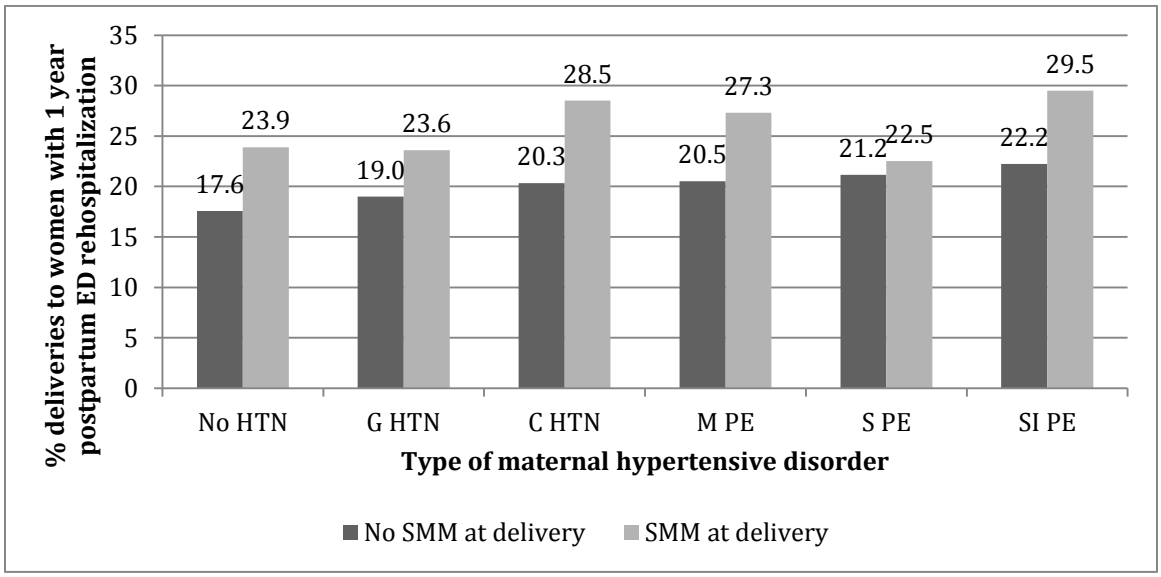
G HTN: Gestational hypertension; C HTN: Chronic hypertension; M PE: Mild preeclampsia; S PE: Severe preeclampsia; SI PE: Superimposed preeclampsia

Figure 4.17 Six Week Postpartum Emergency Department Admissions by Hypertensive Status and Severe Maternal Morbidity, Deliveries to MA Women 2002-2011



G HTN: Gestational hypertension; C HTN: Chronic hypertension; M PE: Mild preeclampsia; S PE: Severe preeclampsia; SI PE: Superimposed preeclampsia

Figure 4.18 One Year Postpartum Emergency Department Admissions by Hypertensive Status and Severe Maternal Morbidity, Deliveries to MA Women 2002-2011



G HTN: Gestational hypertension; C HTN: Chronic hypertension; M PE: Mild preeclampsia; S PE: Severe preeclampsia; SI PE: Superimposed preeclampsia

Main Multivariate Results

Hospital Discharge Rehospitalization

The magnitude of the adjusted risk of HD rehospitalization in the first six weeks was similar among deliveries with SMM and among those with maternal hypertensive disorders. Among those with SMM, the risk of rehospitalization was 2.27 (95% CI: 2.03-2.54); risks did not vary significantly among deliveries to women by subtypes of maternal hypertensive disorders, with a range of 1.79 to 2.25 (**Table 4.21**). Among deliveries to women with other chronic and pregnancy-associated conditions, the risk of HD rehospitalization within six weeks was significantly increased compared to deliveries to women without any conditions, ranging from 1.20 to 1.59.

Within the first year, the adjusted risk of HD rehospitalization remained elevated for deliveries to women with SMM (aRR: 1.95; 95% CI: 1.80-2.11) and for both superimposed preeclampsia and chronic hypertension (**Table 4.22**). The risk estimate was reduced among deliveries to women with other types of maternal hypertension (severe and mild preeclampsia and gestational hypertension) compared to the risk within six weeks. Among other chronic and pregnancy-associated conditions, risks were comparable to risks within six weeks for: pre-existing diabetes, gestational diabetes, asthma, depression, and autoimmune conditions. The risk of HD rehospitalization within one year among deliveries to women with substance use disorders was higher than within six weeks (aRR: 1.89 vs. 1.40).

Table 4.21 Unadjusted and Adjusted Risk of Hospital Discharge Rehospitalization within 6 weeks, Deliveries to MA Women 2002-2011

Characteristic	RR (95% CI)	aRR[1] (95% CI)
SMM25	**4.00 (3.61-4.44)**	**2.27 (2.03-2.54)**

Superimposed preeclampsia	**4.23 (2.51-5.10)**	**2.25 (1.85-2.73)**
Severe preeclampsia	**3.38 (3.00-3.80)**	**1.79 (1.58-2.04)**
Mild preeclampsia	**2.87 (2.62-3.16)**	**2.01 (1.82-2.22)**
Chronic hypertension	**2.47 (2.21-2.77)**	**1.81 (1.61-2.04)**
Gestational hypertension	**2.16 (1.20-2.35)**	**1.87 (1.72-2.03)**
Pre-existing diabetes	**2.36 (2.08-2.68)**	**1.45 (1.27-1.66)**
Gestational diabetes	**1.42 (1.31-1.54)**	**1.20 (1.11-1.30)**
Asthma	**1.55 (1.42-1.70)**	**1.23 (1.12-1.36)**
Substance use disorder	**1.89 (1.67-2.15)**	**1.40 (1.22-1.61)**
Depression	**1.59 (1.44-1.76)**	**1.29 (1.16-1.43)**
Autoimmune disorders	**1.87 (1.55-2.25)**	**1.59 (1.32-1.91)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy

Table 4.22 Unadjusted and Adjusted Risk of Hospital Discharge Rehospitalization within 1 year, Deliveries to MA Women 2002-2011

Characteristic	RR (95% CI)	aRR[1] (95% CI)
SMM25	**2.87 (2.67-3.09)**	**1.95 (1.80-2.11)**
Superimposed preeclampsia	**2.93 (2.55-3.36)**	**1.82 (1.58-2.09)**
Severe preeclampsia	**2.18 (2.00-2.39)**	**1.43 (1.30-1.57)**
Mild preeclampsia	**1.87 (1.75-2.01)**	**1.50 (1.39-1.61)**
Chronic hypertension	**2.03 (1.88-2.19)**	**1.62 (1.50-1.75)**
Gestational hypertension	**1.55 (1.46-1.64)**	**1.44 (1.36-1.53)**
Pre-existing diabetes	**2.27 (2.09-2.47)**	**1.66 (1.52-1.80)**
Gestational diabetes	**1.30 (1.23-1.37)**	**1.20 (1.14-1.27)**
Asthma	**1.75 (1.65-1.85)**	**1.34 (1.26-1.42)**
Substance use disorder	**3.17 (2.97-3.38)**	**1.89 (1.76-2.03)**
Depression	**2.03 (1.92-2.15)**	**1.49 (1.40-1.58)**
Autoimmune disorders	**2.31 (2.08-2.56)**	**2.11 (1.90-2.34)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy

Observational Stay Rehospitalization

The adjusted risk of OS rehospitalization in the first six weeks postpartum was more than double among deliveries to women with SMM at delivery compared to those without (aRR: 2.24; 95% CI: 1.79-2.79) (**Table 4.23**). Deliveries to women with subtypes of hypertensive disorders also had a more than two-fold risk of OS rehospitalization

within six weeks. Deliveries to women with pre-existing diabetes, substance use disorders, and autoimmune conditions were not significantly associated with OS rehospitalization within six weeks. Deliveries to women with gestational diabetes, asthma, and depression were at increased risk but these point estimates were less in magnitude than the risk found for deliveries to women with SMM.

The one-year postpartum risk of OS rehospitalization was still increased for deliveries to women with SMM at delivery (aRR: 1.59; 95% CI: 1.37-1.86) (**Table 4.24**). Compared to six weeks, risk estimates for rehospitalization within one year were decreased among deliveries to women with mild preeclampsia (aRR: 2.50 vs. 1.73) and with gestational hypertension (2.11 vs. 1.65). Risk estimates for rehospitalization among deliveries to women with other types of chronic and pregnancy-associated conditions were all significant at one year, ranging from 1.33 to 1.98, with the highest risks seen for deliveries to women with chronic hypertension and superimposed preeclampsia.

Table 4.23 Unadjusted and Adjusted Risk of Observational Stay Rehospitalization within 6 weeks, Deliveries to MA Women 2002-2011

Characteristic	RR (95% CI)	aRR[1] (95% CI)
SMM25	**3.42 (2.79-4.19)**	**2.24 (1.79-2.79)**
Superimposed preeclampsia	**3.94 (2.74-5.65)**	**2.56 (1.75-3.74)**
Severe preeclampsia	**3.03 (2.41-3.80)**	**2.06 (1.61-2.65)**
Mild preeclampsia	**3.01 (2.55-3.57)**	**2.50 (2.10-2.98)**
Chronic hypertension	**3.13 (2.60-3.77)**	**2.54 (2.10-3.08)**
Gestational hypertension	**2.34 (2.03-2.70)**	**2.11 (1.82-2.44)**
Pre-existing diabetes	**1.70 (1.30-2.23)**	1.09 (0.82-1.44)
Gestational diabetes	**1.45 (1.25-1.68)**	**1.25 (1.08-1.45)**
Asthma	**1.70 (1.44-2.00)**	**1.43 (1.21-1.70)**
Substance use disorder	**1.68 (1.31-2.15)**	1.30 (0.99-1.72)
Depression	**1.83 (1.54-2.17)**	**1.54 (1.28-1.84)**
Autoimmune disorders	1.29 (0.87-1.92)	1.05 (0.70-1.57)

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: p<0.05

Table 4.24 Unadjusted and Adjusted Risk of Observational Stay Rehospitalization within 1 year, Deliveries to MA Women 2002-2011

Characteristic	RR (95% CI)	aRR[1] (95% CI)
SMM25	**2.23 (1.94-2.57)**	**1.59 (1.37-1.86)**
Superimposed preeclampsia	**2.84 (2.25-3.60)**	**1.94 (1.53-2.47)**
Severe preeclampsia	**2.04 (1.75-2.37)**	**1.49 (1.26-1.75)**
Mild preeclampsia	**2.00 (1.79-2.25)**	**1.73 (1.54-1.94)**
Chronic hypertension	**2.44 (2.17-2.74)**	**1.98 (1.76-2.24)**
Gestational hypertension	**1.75 (1.60-1.92)**	**1.65 (1.50-1.81)**
Pre-existing diabetes	**2.20 (1.92-2.53)**	**1.58 (1.37-1.83)**
Gestational diabetes	**1.48 (1.36-1.61)**	**1.38 (1.27-1.51)**
Asthma	**1.87 (1.71-2.04)**	**1.48 (1.35-1.62)**
Substance use disorder	**1.99 (1.74-2.27)**	**1.33 (1.15-1.54)**
Depression	**1.90 (1.72-2.09)**	**1.48 (1.34-1.64)**
Autoimmune disorders	**1.94 (1.60-2.34)**	**1.71 (1.41-2.08)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold p<0.05

Emergency Department Admission

The risk of ED admission within six weeks was increased for deliveries to women with SMM (aRR: 1.45; 95% CI: 1.33-1.57) (**Table 4.25**); it was significantly less than the risk estimate for HD (aRR: 2.27; 95% CI: 2.03-2.54) or OS (aRR: 2.24; 95% CI: 1.79-2.79) rehospitalization within six weeks. For maternal hypertensive disorders, the risk of ED admission ranged from 1.14 to 1.27, with the highest point estimates for deliveries to women with superimposed preeclampsia and chronic hypertension. Women with other chronic and pregnancy-associated conditions also had increased risk of ED admission within six weeks, with the highest risk seen among deliveries to women with substance use disorders (aRR: 1.43; 95% CI: 1.35-1.52).

The risk of ED admission within one year was still increased among deliveries to women with SMM (aRR: 1.16; 95% CI: 1.12-1.21), although it was attenuated from the risk within six weeks (aRR: 1.45; 95% CI: 1.33-1.57) (**Table 4.26**). The risk of admission among deliveries to women with all hypertensive disorder subtypes also remained significant within one year postpartum (aRR range: 1.08-1.22). For other chronic and pregnancy-associated conditions, risks within one year postpartum were similar to those seen within six weeks, with the exception of substance use disorders, which was decreased within one year postpartum compared to six weeks (1.27 vs. 1.43).

Table 4.25 Unadjusted and Adjusted Risk of Emergency Department Rehospitalization within 6 weeks, Deliveries to MA Women 2002-2011

Characteristic	RR (95% CI)	aRR[1] (95% CI)
SMM25	**1.79 (1.65-1.95)**	**1.45 (1.33-1.57)**
Superimposed preeclampsia	**1.43 (1.21-1.69)**	**1.27 (1.07-1.50)**
Severe preeclampsia	**1.49 (1.36-1.63)**	**1.23 (1.12-1.35)**
Mild preeclampsia	**1.30 (1.22-1.40)**	**1.17 (1.09-1.26)**
Chronic hypertension	**1.26 (1.16-1.36)**	**1.27 (1.17-1.38)**
Gestational hypertension	**1.16 (1.10-1.23)**	**1.14 (1.08-1.21)**
Pre-existing diabetes	**1.22 (1.11-1.34)**	**1.16 (1.05-1.28)**
Gestational diabetes	**1.13 (1.08-1.19)**	**1.15 (1.10-1.21)**
Asthma	**1.64 (1.56-1.72)**	**1.34 (1.27-1.41)**
Substance use disorder	**2.90 (2.74-3.07)**	**1.43 (1.35-1.52)**
Depression	**1.78 (1.69-1.87)**	**1.34 (1.27-1.41)**
Autoimmune disorders	**1.16 (1.02-1.31)**	**1.28 (1.13-1.45)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold:$p<0.05$

Table 4.26 Unadjusted and Adjusted Risk of Emergency Department Rehospitalization within 1 year, Deliveries to MA Women 2002-2011

Characteristic	RR (95% CI)	aRR[1] (95% CI)
SMM25	**1.31 (1.26-1.36)**	**1.16 (1.12-1.21)**
Superimposed preeclampsia	**1.27 (1.18-1.37)**	**1.20 (1.11-1.29)**
Severe preeclampsia	**1.19 (1.14-1.24)**	**1.08 (1.03-1.12)**
Mild preeclampsia	**1.16 (1.12-1.20)**	**1.10 (1.07-1.14)**
Chronic hypertension	**1.15 (1.11-1.20)**	**1.22 (1.17-1.26)**

Gestational hypertension	**1.07 (1.05-1.10)**	**1.09 (1.07-1.12)**
Pre-existing diabetes	**1.19 (1.14-1.24)**	**1.20 (1.15-1.25)**
Gestational diabetes	**1.03 (1.01-1.05)**	**1.12 (1.10-1.15)**
Asthma	**1.58 (1.55-1.62)**	**1.30 (1.27-1.33)**
Substance use disorder	**2.25 (2.20-2.31)**	**1.25 (1.22-1.28)**
Depression	**1.59 (1.55-1.62)**	**1.27 (1.24-1.29)**
Autoimmune disorders	**1.15 (1.09-1.21)**	**1.30 (1.24-1.38)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: $p<0.05$

Other covariates in the main regression models were also evaluated and results are presented in **Appendix A**. There were differences in the risks of rehospitalization by hospital type similar to those noted in Aim 2 analyses.

Moderation Effect Results

SMM was assessed as a moderator in the relation between maternal hypertensive disorders and rehospitalization outcomes. First, interaction terms between SMM and maternal hypertensive disorder subtypes were assessed in each of the six main models of rehospitalization. There were five significant interactions found across all outcomes. For hospital discharge rehospitalization: within one year, there was a significant interaction between superimposed preeclampsia and SMM ($p=0.02$); within six weeks, there were significant interactions between SMM and severe preeclampsia ($p=0.004$) as well as SMM and superimposed preeclampsia ($p=0.003$). For observational stay rehospitalization: there was a significant interaction between severe preeclampsia and SMM within one year ($p=0.005$) and within six weeks ($p=0.02$). There were no significant interaction terms between maternal hypertensive disorder subtypes noted for in the risk of emergency department admission.

To further evaluate the potential differential effect of SMM on the relation between subtypes of hypertensive disorders and rehospitalization, stratified analyses were

conducted among deliveries to women with (n=7,815) and without SMM (n=727,761) for hospital discharge (**Table 4.27**) and observational stay outcomes. Superimposed preeclampsia and severe preeclampsia were combined into one category. Due to non-convergence of observational stay outcomes in the stratified analyses, observational stay and hospital discharge outcomes were combined (**Table 4.28**).

Table 4.27 Stratified Analysis of Hospital Discharge Rehospitalization by Severe Maternal Morbidity, Deliveries to MA Women 2002-2011

Type of Rehospitalization	Exposure	No SMM Sample aRR (95% CI)	SMM Sample aRR (95% CI)
HD 1 year	SIPE AND SPE	**1.57 (1.44-1.71)**	1.21 (0.95-1.55)
	Mild Preeclampsia	**1.51 (1.40-1.62)**	**1.35 (1.01-1.81)**
	Chronic HTN	**1.61 (1.49-1.75)**	**1.70 (1.23-2.36)**
	Gestational HTN	**1.44 (1.36-1.53)**	**1.37 (1.02-1.86)**
	Pre-existing diabetes	**1.68 (1.54-1.83)**	**1.44 (1.05-2.00)**
	Gestational diabetes	**1.20 (1.14-1.27)**	1.15 (0.86-1.53)
	Asthma	**1.34 (1.27-1.43)**	1.24 (0.94-1.63)
	Substance Use	**1.91 (1.77-2.05)**	**1.46 (1.02-2.10)**
	Depression	**1.51 (1.42-1.60)**	0.97 (0.70-1.36)
	Autoimmune	**2.15 (1.94-2.39)**	1.47 (0.92-2.29)
HD 6 weeks	SIPE and SPE	**1.99 (1.77-2.24)**	**1.45 (1.06-1.99)**
	Mild Preeclampsia	**2.03 (1.84-2.25)**	**1.67 (1.15-2.43)**
	Chronic HTN	**1.79 (1.59-2.03)**	**1.93 (1.21-3.09)**
	Gestational HTN	**1.89 (1.74-2.05)**	1.47 (0.98-2.21)
	Pre-existing diabetes	**1.51 (1.32-1.73)**	0.99 (0.57-1.72)
	Gestational diabetes	**1.21 (1.11-1.31)**	1.09 (0.72-1.63)
	Asthma	**1.24 (1.12-1.36)**	1.21 (0.80-1.83)
	Substance Use	**1.37 (1.19-1.59)**	**1.81 (1.07-3.05)**
	Depression	**1.33 (1.20-1.48)**	0.56 (0.30-1.05)
	Autoimmune	**1.68 (1.39-2.03)**	0.70 (0.30-1.67)

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: $p<0.05$

Table 4.28 Stratified Analysis of Hospital Discharge/Observational Stay Rehospitalization by Severe Maternal Morbidity, Deliveries to MA Women 2002-2011

Type of Rehospitalization	Exposure	No SMM Sample aRR (95% CI)	SMM Sample aRR (95% CI)
HD/OS 1 year	SIPE AND SPE	**1.57 (1.46-1.70)**	1.20 (0.96-1.50)
	Mild Preeclampsia	**1.55 (1.45-1.65)**	**1.43 (1.11-1.84)**

	Chronic HTN	**1.71 (1.59-1.83)**	**1.85 (1.40-2.46)**
	Gestational HTN	**1.50 (1.42-1.58)**	**1.36 (1.04-1.79)**
	Pre-existing diabetes	**1.65 (1.53-1.77)**	1.31 (0.97-1.77)
	Gestational diabetes	**1.25 (1.19-1.31)**	1.20 (0.93-1.55)
	Asthma	**1.37 (1.30-1.85)**	1.22 (0.94-1.57)
	Substance Use	**1.73 (1.62-1.85)**	1.24 (0.87-1.75)
	Depression	**1.49 (1.41-1.57)**	1.03 (0.77-1.39)
	Autoimmune	**2.00 (1.82-2.20)**	1.36 (0.90-2.07)
HD/OS 6 weeks	SIPE and SPE	**2.07 (1.87-2.30)**	**1.41 (1.06-1.88)**
	Mild Preeclampsia	**2.11 (1.93-2.31)**	**1.69 (1.22-2.35)**
	Chronic HTN	**1.96 (1.76-2.18)**	**2.08 (1.38-3.13)**
	Gestational HTN	**1.95 (1.81-2.10)**	1.43 (0.99-2.06)
	Pre-existing diabetes	**1.42 (1.26-1.61)**	0.86 (0.51-1.45)
	Gestational diabetes	**1.23 (1.14-1.32)**	1.13 (0.79-1.60)
	Asthma	**1.29 (1.18-1.40)**	1.23 (0.85-1.78)
	Substance Use	**1.36 (1.19-1.55)**	1.27 (0.75-2.15)
	Depression	**1.37 (1.25-1.50)**	0.78 (0.48-1.27)
	Autoimmune	**1.49 (1.25-1.78)**	0.92 (0.47-1.82)

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: $p<0.05$

To aid in interpreting the relation between chronic and pregnancy-associated conditions, SMM at delivery, and rehospitalization, mutually exclusive categories of chronic conditions and SMM at delivery were constructed. First, to understand the relation between hypertensive disorders and SMM, a variable was created for mutually exclusive combinations of severe forms of maternal hypertensive disorders (superimposed preeclampsia and severe preeclampsia), other forms of maternal hypertensive disorders (mild preeclampsia, chronic hypertension, and gestational hypertension), and SMM at delivery, **Table 4.29** shows the result of the analysis of this variable. Compared to deliveries to women without hypertensive disorders and without SMM at delivery, deliveries to women with only SMM indicated at delivery had an increased risk of HD rehospitalization compared to deliveries to women with only subtypes of hypertensive disorders both within six weeks and one year; their confidence

intervals did not overlap. Point estimates for rehospitalization risk were generally greater when both hypertensive disorders and SMM were indicated; within six weeks there was a greater than 3-fold risk in HD rehospitalization among deliveries to women with SMM and hypertensive compared to those without either; only the estimate for SMM and other HTN differed from the estimates for SMM alone of the HTN groups with no SMM.

Table 4.29 Adjusted Risk of Rehospitalization by both Maternal Hypertensive Disorders and Severe Maternal Morbidity, Deliveries to MA Women 2002-2011

New Variable Categorization: Severe Hypertension, Other Hypertension, and SMM	Hospital Discharge 6 week aRR[1] (95% CI)	Hospital Discharge 1 year aRR[1] (95% CI)
No HTN and No SMM	REF	REF
SMM, No HTN	**2.60 (2.28-2.98)**	**2.06 (1.87-2.26)**
Severe HTN, No SMM	**2.03 (1.80-2.27)**	**1.58 (1.45-1.72)**
Other HTN, No SMM	**1.92 (1.81-2.05)**	**1.50 (1.44-1.57)**
SMM and Severe HTN	**3.09 (2.34-4.10)**	**2.34 (1.89-2.91)**
SMM and Other HTN	**3.88 (3.10-4.86)**	**2.87 (2.42-3.39)**
	Observational Stay 6 week aRR[1] (95% CI)	Observational Stay 1 year aRR[1] (95% CI)
No HTN and No SMM	REF	REF
SMM, No HTN	**2.78 (2.15-3.60)**	**1.69 (1.41-2.03)**
Severe HTN, No SMM	**2.40 (1.93-2.99)**	**1.66 (1.44-1.92)**
Other HTN, No SMM	**2.35 (2.11-2.62)**	**1.75 (1.63-1.87)**
SMM and Severe HTN	**2.43 (1.21-4.90)**	**1.90 (1.23-2.94)**
SMM and Other HTN	**4.43 (2.84-6.92)**	**2.80 (2.06-3.82)**
	Emergency Department 6 week aRR[1] (95% CI)	Emergency Department 1 year aRR[1] (95% CI)
0 No HTN and No SMM	REF	REF
1 SMM, No HTN	**1.51 (1.37-1.66)**	**1.18 (1.13-1.23)**
2 Severe HTN, No SMM	**1.27 (1.16-1.38)**	**1.11 (1.07-1.16)**
3 Other HTN, No SMM	**1.18 (1.13-1.23)**	**1.12 (1.10-1.14)**
4 SMM and Severe HTN	**1.46 (1.12-1.90)**	**1.21 (1.07-1.37)**
5 SMM and Other HTN	**1.61 (1.30-1.98)**	**1.27 (1.16-1.40)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, autoimmune conditions, asthma, pre-existing and gestational diabetes, substance use disorder, depression

Another categorization examined the role of pre-existing chronic medical conditions (chronic hypertension, superimposed preeclampsia, autoimmune conditions,

asthma, and pre-existing diabetes) (PECMC), pregnancy-associated conditions (mild and severe preeclampsia, gestational hypertension and gestational diabetes) (PAC), and SMM at delivery (**Table 4.30**). Compared to deliveries to women without SMM, PAC and PECMC, the risk of HD rehospitalization within six weeks was greater for those with just SMM at delivery compared to women with just PAC or just PECMC. The addition of PAC or PECMC, or both to SMM did not increase the risk for six-week rehospitalization compared to deliveries to women with just SMM. For one-year rehospitalization, the risk estimate was decreased compared to the risk at six weeks for deliveries to women with just SMM (2.73 to 2.10) or just PAC (1.72 to1.40); however, the risk stayed constant for those with PECMC. The risk of 1 year HD rehospitalization was greater for deliveries to women with just SMM compared to deliveries to women with just PAC or just PECMC. Deliveries to women with both SMM with PECMC had a greater risk of one-year HD rehospitalization than with just SMM or just PECMC.

Table 4.30 Adjusted Risk of Rehospitalization by Pre-Existing Chronic Medical Conditions, Pregnancy-Associated Conditions and Severe Maternal Morbidity, Deliveries to MA Women

Variable categorization: SMM, PAC, PECMC[1]	6 week HD aRR[2] (95% CI)	1 year HD aRR[2] (95% CI)
No SMM, no PAC, no PECMC	REF	REF
SMM, no PAC, no PECMC	**2.73 (2.37-3.16)**	**2.10 (1.89-2.33)**
No SMM, PAC, no PECMC	**1.72 (1.62-1.82)**	**1.40 (1.35-1.46)**
No SMM, no PAC, PECMC	**1.64 (1.52-1.77)**	**1.67 (1.60-1.75)**
SMM, PAC, no PECMC	**3.45 (2.82-4.22)**	**2.61 (2.23-3.04)**
SMM, no PAC, PECMC	**3.20 (2.37-4.30)**	**3.30 (2.74-3.96)**
No SMM, PAC, PECMC	**2.27 (1.98-2.60)**	**2.08 (1.90-2.27)**
SMM, PAC, PECMC	**3.41 (2.11-5.49)**	**2.83 (2.01-3.98)**
	6 week OS aRR (95% CI)	1 year OS aRR (95% CI)
No SMM, no PAC, no PECMC	REF	REF
SMM, no PAC, no PECMC	**2.82 (2.13-3.73)**	**1.85 (1.52-2.25)**
No SMM, PAC, no PECMC	**2.00 (1.80-2.21)**	**1.64 (1.54-1.75)**
No SMM, no PAC, PECMC	**1.87 (1.64-2.13)**	**1.82 (1.69-1.96)**
SMM, PAC, no PECMC	**3.40 (2.22-5.21)**	**1.98 (1.43-2.74)**
SMM, no PAC, PECMC	**3.43 (1.88-6.24)**	**2.90 (2.02-4.16)**

No SMM, PAC, PECMC	**2.42 (1.87-3.14)**	**2.34 (2.02-2.71)**
SMM, PAC, PECMC	**4.76 (1.98-11.49)**	**3.22 (1.74-5.94)**
	6 week ED aRR (95% CI)	1 year ED aRR (95% CI)
No SMM, no PAC, no PECMC	REF	REF
SMM, no PAC, no PECMC	**1.50 (1.35-1.66)**	**1.18 (1.12-1.24)**
No SMM, PAC, no PECMC	**1.17 (1.13-1.21)**	**1.12 (1.10-1.13)**
No SMM, no PAC, PECMC	**1.33 (1.27-1.39)**	**1.30 (1.28-1.33)**
SMM, PAC, no PECMC	**1.68 (1.41-2.00)**	**1.31 (1.20-1.42)**
SMM, no PAC, PECMC	**2.04 (1.63-2.55)**	**1.51 (1.36-1.67)**
No SMM, PAC, PECMC	**1.56 (1.42-1.70)**	**1.40 (1.35-1.46)**
SMM, PAC, PECMC	**1.15 (0.69-1.93)**	**1.30 (1.06-1.59)**

[1]SMM: Severe maternal morbidity at delivery; PAC: Pregnancy-associated conditions; PECMC: Pre-existing chronic medical conditions

[2]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, depression, substance use disorder

Additional categorizations for depression and substance use disorder with SMM at delivery can be found in **Appendix B**.

Sensitivity Analyses

Severe Maternal Morbidity without Blood Transfusion

SMM was also analyzed in all multivariable regressions without the blood transfusion indicator. The risk of HD rehospitalization within six weeks was decreased among deliveries to women with SMM without transfusion (aRR: 1.75; 95% CI: 1.52-2.02) compared to SMM with transfusion (aRR: 2.27; 95% CI: 2.03-2.54) (**Table 4.31**). For all other types of rehospitalization outcomes, the risk did not did not differ by the inclusion or exclusion of the blood transfusion indicator in the SMM measure.

Table 4.31 Aim 3 Sensitivity Analysis: Severe Maternal Morbidity with and without Blood Transfusion

	HD 6 wks aRR[1] (95% CI)	HD 1 year aRR[1] (95% CI)	OS 6 wks aRR[1] (95% CI)	OS 1 yr aRR[1] (95% CI)	ED 6 wks aRR[1] (95% CI)	ED 1 yr aRR[1] (95% CI)
SMM without transfusion	**1.75 (1.52-2.02)**	**1.69 (1.53-1.87)**	**2.08 (1.60-2.71)**	**1.59 (1.32-1.90)**	**1.39 (1.25-1.54)**	**1.18 (1.12-1.23)**
SMM with transfusion	**2.27 (2.03-2.54)**	**1.95 (1.80-2.11)**	**2.24 (1.79-2.79)**	**1.59 (1.37-1.86)**	**1.45 1.33-1.57)**	**1.16 (1.12-1.21)**

HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department
Bold: p<0.05

Number of Severe Maternal Morbidity Indicators

In this analysis, we also examined SMM by the number of SMM indicators a woman had at delivery hospitalization; 1.11% (n=8,135) of women had only one SMM indicator at delivery hospitalization and 0.19% (n=1,426) of women with two or more SMM indicators. There was no difference in the risk of rehospitalization with increasing number of SMM indicators (**Table 4.32**).

Table 4.32 Aim 3 Sensitivity Analysis: Number of Severe Maternal Morbidity Indicators

	HD 6 wks aRR[1] (95% CI)	HD 1 year aRR[1] (95% CI)	OS 6 wks aRR[1] (95% CI)	OS 1 yr aRR[1] (95% CI)	ED 6 wks aRR[1] (95% CI)	ED 1 yr aRR[1] (95% CI)
No SMM	REF	REF	REF	REF	REF	REF
1 SMM	**2.14 (1.91-2.40)**	**1.81 (1.67-1.97)**	**2.33 (2.07-2.62)**	**1.60 (1.36-1.89)**	**1.47 (1.34-1.60)**	**1.16 (1.12-1.22)**
2+ SMM	**1.97 (1.54-2.53)**	**2.02 (1.72-2.39)**	**1.97 (1.50-2.57)**	**1.55 (1.07-2.22)**	**1.34 (1.08-1.67)**	**1.16 (1.05-1.29)**

HD: Hospital Discharge; OS: Observational Stay; ED: Emergency Department
[1] Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, chronic and pregnancy-associated conditions (maternal hypertensive disorders, pre-existing and gestational diabetes, asthma, substance use disorder, depression, autoimmune disorders)
Bold: p<0.05

Severe Maternal Morbidity as a Mediator

The analysis assessed if SMM moderated the relation between chronic and pregnancy-associated conditions and rehospitalization. To examine an alternate hypothesis that SMM mediated the relation between chronic and pregnancy-associated conditions and rehospitalization within the first year postpartum, analyses were conducted in accordance with the methodology proposed by Baron and Kenney. First, a model estimated the relation between SMM and each of the six rehospitalization outcomes, as performed in Aim 2. Second, a model estimated the relation between

chronic and pregnancy-associated conditions and rehospitalization outcomes. The third and final model estimated the risk of rehospitalization with both chronic and pregnancy-associated conditions and SMM, as seen above in the Aim 3 main multivariable results. Results of the mediation analysis are shown in **Appendix C**. There was no evidence of SMM mediation in any of the rehospitalization outcomes as the coefficients for chronic and pregnancy-associated conditions did not change between Models 2 and 3.

In summary, between 2000-2012, maternal hypertensive disorders were documented in 8.7% of deliveries and the SMM rate was 101.9 per 10,000 deliveries in Massachusetts. From 2002-2011, 5.2% of all deliveries to women had a least one rehospitalization within six weeks and 19.9% within one year postpartum. Hypertensive disorders and other chronic conditions increased the odds of SMM at delivery and the risk of rehospitalization up to one year postpartum. Rehospitalization risk varied by type of admission and hypertensive subtype. SMM at delivery independently increased rehospitalization risk within the first six weeks and year postpartum and slightly moderated the relation between hypertensive disorders and rehospitalization.

Chapter Five: Discussion

Overview

This chapter discusses the results of the three aims of the research reported in this dissertation. The aims were to: 1) evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with severe maternal morbidity at delivery; 2) evaluate the relation between severe maternal morbidity at delivery and postpartum maternal rehospitalization in the year following delivery among deliveries to women without chronic medical diseases; and 3) evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with postpartum maternal rehospitalization in the year following delivery independent of severe maternal morbidity at delivery. The chapter begins with a brief overview of the study methods, a discussion of the main findings for each aim, followed by a discussion of strengths and limitations, public health implications and conclusions of the research.

Study Overview

Aim 1 evaluated the relation between maternal hypertensive disorders, pre-existing and gestational diabetes, asthma, depression, substance use disorders and autoimmune conditions and severe maternal morbidity (SMM) at the delivery hospitalization. The study population was identified as deliveries to resident women in Massachusetts over a 13-year period. Birth certificates and fetal death records (BCFD) were linked to delivery-related hospital discharge (HDD) records in Massachusetts from 2000-2012, using the Pregnancy to Early Life Longitudinal (PELL) data system (n=960,982). SMM was defined using the CDC classification system of 25 ICD-9-CM diagnoses and procedures codes on HDD records, adjusted for severity-based on length

of stay for method of delivery; it was examined with and without blood transfusion. Bivariate comparisons were assessed with Wald χ^2 tests and trends over time were assessed with Cochran-Armitage tests. Multivariate logistic regression using generalized estimating equations examined the odds of SMM with and without blood transfusion at delivery hospitalization. Main covariates included: maternal age, race/ethnicity, insurance status, and hospital level.

Aim 2 evaluated the association between SMM at delivery hospitalization and hospital utilization in the first six weeks and one year postpartum. Non-injury non-antenatal emergency department (ED), observational stay (OS) and non-delivery hospital discharge (HD) records in the first year postpartum were linked to corresponding BCFD and HDD deliveries from 2002-2011. Aim 2 was based on data for a subset of deliveries to women without chronic medical conditions (superimposed preeclampsia, chronic hypertension, diabetes, asthma, and autoimmune conditions) (n=685,228). Analyses described types of hospital encounters in the first six weeks and year postpartum by timing and frequency. Wald χ^2 test statistics were used to assess differences in postpartum hospital encounters between deliveries with and without SMM. Multivariate log-binomial regression with generalized estimating equations modeled the relative risk of hospital encounters within six weeks and one year postpartum, adjusting for key confounding variables including year, hospital level, maternal age, race/ethnicity, insurance payer, pregnancy-specific conditions, method of delivery, and length of stay at delivery.

Aim 3 evaluated the association between maternal hypertensive disorders, other chronic and pregnancy-associated conditions, SMM and postpartum maternal

rehospitalization in the year following delivery. We also evaluated whether SMM at delivery moderated the relation between maternal hypertensive disorders and rehospitalization. Non-injury non-antenatal ED, OS and HD records in the first year postpartum were linked to all corresponding BCFD and HDD Massachusetts deliveries from 2002-2011, using the PELL data system (n=735,576). Multivariate Poisson regression models used a generalized estimating equations approach to estimate the risk of each type of rehospitalization within six weeks and one year postpartum. Effect modification was examined through interaction terms in multivariate models between hypertensive disorder subtypes and SMM at delivery, with significance assessed at $p<0.05$.

Aim 1 Discussion

Aim 1: Evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with severe maternal morbidity outcomes at delivery.

Maternal hypertensive disorders were documented in 8.7% of delivery hospitalizations; the most common subtype was gestational hypertension (3.7%). The SMM rate was 101.9 per 10,000 deliveries. Our study results showed increased odds of SMM at delivery among all subtypes of maternal hypertensive disorders in pregnancy and some chronic conditions. Analyses of trends in hypertensive disorders among deliveries between 2000 and 2012 are consistent with previous findings of recent increasing rates of maternal hypertensive disorders, with the exception of mild preeclampsia (1-5). The increase in the SMM rate over the study period also is consistent with previous research, although we report more recent data, inclusive of 2012, showing

a continuation of increasing SMM rates (6). A further recalculation of the SMM rate without blood transfusion also showed increases over the study period; this rate showed a somewhat lower increase over time.

SMM was more frequent among deliveries to women with all hypertensive subtypes when compared to deliveries for women without a hypertension diagnosis. Deliveries to women with the most severe maternal hypertensive disorders had the greatest odds of SMM after adjustment for social and biological confounders. Compared to women without hypertension, the odds of SMM were 4.08 (95% CI: 3.71-4.48) for women with severe preeclampsia, 2.65 (95% CI: 2.23-3.15) for superimposed preeclampsia, 2.30 (95% CI: 2.09-2.53) for mild preeclampsia, 1.60 (95% CI: 1.46-1.75) for gestational hypertension and 1.50 (95% CI: 1.32-1.70) for chronic hypertension. When blood transfusion was excluded, there were no considerable changes in the odds of SMM by hypertensive disorder type.

Previous research examining hypertensive disorders and obstetric complications showed the highest risk to be among deliveries to women with severe preeclampsia and the lowest among those with gestational hypertension (3), although superimposed preeclampsia was not considered. A recent study of 15 California hospitals found 8.8% of deliveries to women with acute severe intrapartum hypertension (systolic blood pressure >160mm Hg or diastolic blood pressure >105 mm Hg) had SMM at delivery compared to 2.3% without this complication (7).

The observed association between severe preeclampsia and SMM at delivery is biologically plausible. Some conditions in the SMM classification system including cardiac arrest, acute myocardial infarction and heart failure, may represent complications

of hypertensive disorders (8, 9). Severe preeclampsia may also lead to increased risk of hemorrhage requiring transfusion, a qualifying procedure of SMM, due to decreased blood flow to organs other than the placenta (10). Another indicator in the measure of SMM is amniotic fluid embolism, which is hypothesized to be related to placental structural or physiologic abnormalities, also a leading theory of preeclampsia (11). These explanations may apply to superimposed and mild preeclampsia, as well.

A cardiac-related SMM code was created to further understand potential pathways from hypertensive disorders to SMM. Deliveries to women with severe preeclampsia had increased odds of cardiac-related SMM. The odds of cardiac-related SMM were similar to those of overall SMM for superimposed preeclampsia and chronic hypertension but were attenuated for severe and mild preeclampsia; the odds of cardiac-related SMM were not significant for gestational hypertension. As the definition of severe maternal morbidity is broad, conditions and procedures in this classification system related to cardiovascular illness represent a plausible pathway of the manifestation of hypertensive disorders due to damage to the endothelium (8, 9), as suggested by the results for severe preeclampsia in particular.

Asthma, pre-existing diabetes, and autoimmune conditions were also associated with SMM, both with and without blood transfusion. Although we could not account for disease severity or the extent of medication management, previous research shows adverse perinatal outcomes for women with these conditions. A previous review and meta-analysis indicated that pregnant women with asthma have altered placental function as well as an increased risk of hemorrhage, placental abruption, and premature rupture of the membranes (12). Pre-existing diabetes also has been shown to be associated with

increased risk of preterm delivery and cesarean delivery (13). Types of autoimmune conditions have been associated with poor obstetric outcomes; lupus is associated with cesarean delivery and preterm birth and rheumatoid arthritis is associated with increased risk of cesarean delivery; however, there have been mixed findings regarding adverse outcomes with multiple sclerosis (14).

Both substance use disorders and depression showed increased adjusted odds of SMM overall; however, when sensitivity analyses examined SMM without blood transfusion, both were no longer statistically significant. Opioid use and dependency in pregnancy has been associated with increased odds of transfusion (15), which may explain why substance use disorders were no longer statistically significant when transfusion was omitted. In a study of Medicaid data in the US, antidepressant use late in pregnancy was associated with increased risk of postpartum hemorrhage. While our study did not account for medication use, the lack of a relation between depression and SMM when transfusion was excluded (aOR of SMM with transfusion reduced from 1.24 (95% CI: 1.11-1.38) to 1.12 (95% CI: 0.95-1.32) without transfusion) may be due to the relation of antidepressant medication in depressed women with transfusion (16).

Gestational diabetes was not associated with increased odds of any type of SMM. The unadjusted odds of gestational diabetes was 1.15 (95% CI: 1.06-1.24); the relation between gestational diabetes and SMM was no longer significant when maternal characteristics, including age, race/ethnicity, parity, education, and year were added to the model. While gestational diabetes is a risk factor for some perinatal complications, including macrosomia and cesarean delivery, it does not appear to be associated with SMM (17). It is not generally associated with preterm birth or low birthweight.

Similar to other studies, social and biological variables associated with increased risk of SMM included: maternal age greater than 35 years, non-white race, multiple gestations, cesarean or VBAC delivery, public insurance, no prenatal care, and low birth weight delivery (18, 19). Variables associated with decreased risk of SMM included post-graduate education and smoking during pregnancy; this protective association between smoking and SMM has also been reported for smoking and preeclampsia (20). Obesity was another variable of interest; however, accurate information could not be ascertained across the study period and therefore was not included in the analysis. In a previous study of SMM in New York City from 2011-2013, deliveries to women with overweight and obese pre-pregnancy body mass indices were not at increased odds of SMM compared to deliveries to women at normal weight (21).

Aim 2 and Aim 3 Discussion

Aim 2: Evaluate the relation between severe maternal morbidity at delivery and postpartum maternal rehospitalization in the year following delivery among women without chronic medical diseases.

Aim 3: Evaluate the relation between maternal hypertensive disorders and other chronic and pregnancy-associated conditions in pregnancy with postpartum maternal rehospitalization in the year following delivery independent of severe maternal morbidity at delivery.

Aim 2 was evaluated using the population of deliveries to women without chronic medical conditions. Findings included an increased risk of rehospitalization within six weeks and one year postpartum among deliveries to women with SMM, independent of social and biological confounders in this population. When expanded to include all

women with deliveries in Massachusetts, Aim 3 results showed that deliveries to women with maternal hypertensive disorders and to women with SMM at delivery had increased risk of all types rehospitalization; deliveries to women with chronic medical and pregnancy-associated conditions also had increased risk of rehospitalization within one year. In adjusted analyses, there was some evidence that SMM moderated the relation between maternal hypertensive disorders and types of rehospitalization but this evidence was not strong. Also, SMM did not appear to mediate the relation between maternal hypertensive disorders and types of rehospitalization. When considered together, SMM at delivery appeared to show a stronger effect on HD rehospitalization than maternal hypertensive disorders, as determined by the risk ratios when considered together.

Maternal rehospitalization

Maternal rehospitalization is an indicator of maternal morbidity. The rate of HD non-injury non-antenatal rehospitalization among all postpartum women in the first 42 days in our study (1.2%) was comparable to other studies. Belfort et al. (2010) found 1.2% readmission within 42 days among a system of 114 hospitals in 21 states in the US (22). Liu et al. (2005) found 1.8% of Canadian women with singleton births were rehospitalized within 60 days after initial discharge (23) and Lydon-Rochelle et al. (2000) found an overall readmission rate within 60 days of 1.2% in Washington State (24). In addition to measuring HD rehospitalizations, our study also analyzed OS rehospitalization and ED admission rates to provide a wider range of maternal morbidity in the postpartum period; in the first six weeks, 0.4% of women had at least one OS rehospitalization and 4.0% had at least one ED admission.

Rehospitalization in the first year postpartum was examined to mirror current definitions of pregnancy-related mortality in the US. Approximately one in five women had at least one ED, OS, or HD rehospitalization within the first year postpartum; 17.9% had an ED admission, 1.1% had an OS rehospitalization, and 3.0% had an HD rehospitalization. There was also a trend of increasing HD and ED admissions within the first year postpartum. One Maryland study of reproductive age women aged 15-44 years also found an increasing rate of ED admissions from 2.8 per 100 women in 1999 to 4.2 in 2005 (25).

Severe maternal morbidity and rehospitalization

In our analysis, the risk of at least one rehospitalization within six weeks postpartum was higher among deliveries to women with SMM at delivery hospitalization. Almost three in ten women with SMM at delivery (28.3%) had at least one rehospitalization within the first year postpartum compared to two in ten (19.2%) without SMM.

Most studies of delivery events and rehospitalization focused on the impact of method of delivery. Lyndon et al. (2012) (19) as well as the results for Aim 1 showed an association between cesarean delivery and SMM at delivery. Among primiparous women without chronic medical conditions delivering singleton infants in Washington State, researchers found an 80% increased risk of rehospitalization within 60 days for women with cesarean delivery and 30% increased risk for women with assisted vaginal delivery (24). In a population of women with no prior cesarean and no prenatal risk identified on the birth certificate, DeClercq et al. (2007) found a greater than two-fold risk of rehospitalization in the first 30 days postpartum for women with planned cesarean births

compared to those with planned vaginal births (26). In a case control study, Sharvit et al. (2014) found increased risk of rehospitalization within 14 days associated with emergency cesarean delivery (27). Aim 2 results showed that primary and repeat cesarean deliveries were associated with only a 10-30% increase in HD and ED rehospitalization compared to vaginal deliveries, less than previous studies. In addition to the method of delivery, SMM at delivery was associated with a greater than two-fold increase risk of both HD (aRR 2.48; 95% CI: 2.20-2.80) and OS (aRR 2.47; 95% CI: 1.94-3.14) rehospitalization and approximately a 50% increased risk (aRR: 1.47; 95% CI: 1.34-1.61) in ED admission within the first six weeks postpartum.

The findings also showed a sustained increased risk for rehospitalization for deliveries to women with SMM at delivery up to one year postpartum. Within one year, the risk of HD rehospitalization for deliveries to women with SMM was greater than two-fold compared to women without SMM (aRR: 2.04; 95% CI: 1.87-2.23). Few studies have examined rehospitalization up to one year postpartum. The adjusted odds of rehospitalization between 181-365 days was 1.77 (95% CI: 1.32-2.38) among women with cesarean births with no labor and no complications compared to vaginal births with labor in a study by DeClercq et al. (2007) using linked hospital discharge and vital records data from 1998-2003 (26). The analyses in Aims 2 and 3 looked beyond method of delivery to consider whether or not severe events at delivery adversely impact maternal health in the first year postpartum.

The association between SMM and OS and ED admissions within the first year was less clear. Although OS regression models showed increased risk for SMM within the first year (aRR: 1.57; 95% CI: 1.21-2.03), it is likely due to relation for OS

admissions in the first six weeks. SMM was not significant in adjusted relative risk models for OS admissions between 42-364 days postpartum. For ED admissions within one year, deliveries to women with SMM had a 16% greater risk than those to women without SMM (aRR: 1.16; 95% CI: 1.11-1.21); between 42-365 days, the increased risk of ED admission was only 8% and was not significant when SMM was considered without transfusion.

The observed association of SMM with increased risk of rehospitalizations in this study is consistent with previous studies of readmission associated with certain SMM indicators. A 2010 study by Belfort et al. examined causes of hospital readmission within 42 days postpartum and found the following SMM indicators as reasons for readmission: hemorrhage, sepsis, cardiomyopathy, deep vein thrombosis, and infection (22). Sutton et al. (2010), using data from the Healthcare Cost and Utilization Project (HCUP) State Inpatient Databases (SID) in seven states, found increased hospital readmission within thirty days among patients with a principal or secondary initial diagnosis of septicemia, a SMM indicator (28). Pelvic infections were also found to be the most common type of infection after hysterectomy, another indicator for SMM (29). Callaghan et al. reported a rate of postpartum SMM, 29 per 10,000 deliveries in 2008-2009, based on hospital discharge coding of postpartum hospitalizations in the Nationwide Inpatient Sample; however, these data were not linked to delivery events (6).

Sensitivity analyses were conducted to examine SMM with and without blood transfusion in relation to rehospitalization. Risk estimates were not significantly different when SMM excluded blood transfusion for all postpartum outcomes; however, there was a lower risk of 42-364 day HD readmission among deliveries to women with SMM at

delivery when compared to <42 days HD admission when transfusion was included. This result may be due to greater power to detect differences because of the larger numerator when SMM included transfusion. An additional sensitivity analysis excluded women who died within the first year postpartum, which also showed no difference in risk estimates.

Maternal hypertensive disorders and rehospitalization

The findings from Aim 3 indicated an increased risk of all types of rehospitalization among women with maternal hypertensive disorders and other chronic and pregnancy-associated conditions. Risk, however, varied by type of rehospitalization and by hypertensive subtype. The adjusted risk of HD rehospitalization among deliveries to women with hypertensive disorders ranged from 1.81-2.25 within six weeks and 1.44-1.82 within one year, with the greatest risk seen for superimposed preeclampsia. While no other studies have examined all types of maternal hypertensive disorders, one New York population-based study showed increased odds of cardiovascular disease and stroke-related hospitalizations in the first year postpartum among women with pregnancy-induced hypertension (30). Findings from a study of high-risk women indicated that 17% of women were rehospitalized within one year, with the highest risks of rehospitalization for chronic hypertensives and gestational diabetics (31). In another study, hypertension was one of the most common indications for readmission within six weeks among both vaginal (16.4 per 10,000) and cesarean (23.9 per 10,000) deliveries (22). In our study, risks were similar for HD and OS rehospitalizations within six weeks and one year: both superimposed preeclampsia and chronic hypertension, the two types of pre-pregnancy hypertension, showed the strongest associations with rehospitalizations, emphasizing the role of chronic disease in the postpartum period. All forms of

hypertensive disorders, including those diagnosed during pregnancy, still were associated with increased risk of HD rehospitalizations, indicating a continuation of risk through one year postpartum.

The study results also showed increased risk of ED admissions among deliveries to women with hypertensive disorders, with the highest risk estimates at both six weeks and one year among those with superimposed preeclampsia and chronic hypertension. The risks ranged from 1.14-1.27 within six weeks and 1.08-1.22 within one year and were significantly lower than the risk estimates for HD and OS rehospitalization within six weeks and HD rehospitalization within one year. While other studies have not examined the role of specific hypertensive disorders, a study of Maryland women on Medicaid found the presence of any preconception medical comorbidities (including type 2 diabetes, chronic hypertension, obesity, asthma, mental health, and substance abuse diagnoses) to be associated with increased postpartum ER use in the first six months postpartum (OR 1.61: 95% CI: 1.51-1.73) (32). Although the magnitude of the risk of ED admission is low in comparison to other types of rehospitalization, the adverse effects of maternal hypertensive disorders were still significant up to one year postpartum.

Other chronic and pregnancy-associated conditions and rehospitalization

Pre-existing diabetes, gestational diabetes, asthma, substance use disorders, depression and autoimmune conditions were all associated with an increased risk of HD rehospitalization and ED admission at both time points; some also were associated with increased risk of OS rehospitalization.

Diabetes: Pre-existing diabetes and gestational diabetes were, in general, associated with increased risk of all types rehospitalization with risk estimates ranging between 1.12 and

2.11; the risk was greater for deliveries to women with pre-existing diabetes across all outcomes. Roughly half of women with a history of gestational diabetes will develop Type 2 diabetes within ten years (33). Researchers have found increased odds of Type 1 and Type 2 diabetes hospitalizations in the year after delivery among women with gestational diabetes (30). There is mixed evidence of an association between gestational diabetes and cardiovascular disease (30, 34).

Asthma: A continuation of increased risk of all types of rehospitalization was noted for asthma through one year postpartum, with risks ranging from 1.23 to 1.48. Women with asthma in pregnancy have altered placental function (35); Aim 1 results showed an increased risk of SMM at delivery. In a previous meta-analysis, women with asthma were at increased risk of other maternal and placental complications, including postpartum hemorrhage (RR: 1.29; 95% CI: 1.18-1.41) (12), which could be a cause of rehospitalization.

Autoimmune conditions: Deliveries to women with autoimmune disorders were at increased risk of all types of rehospitalization within one year, ranging from 1.30 to 2.11; point estimates increased between 6 weeks and one year postpartum. Previous studies suggest that some autoimmune disorders, including multiple sclerosis and rheumatoid arthritis, remit during pregnancy but exacerbate in the postpartum period (36-38).

Substance use disorders: Deliveries to women with substance use disorders had 1.89 times the risk of HD rehospitalization within the first year postpartum, significantly higher than the risk at six weeks (aRR: 1.40; 95% CI: 1.22-1.61). Previous studies suggest postpartum substance users (illicit drugs, cigarettes, and alcohol) relapse after

increased rates of abstention during the pregnancy (39), which could lead to increased rehospitalization in the postpartum period.

Depression: Deliveries to women with depression were at increased risk for all types of rehospitalization one year postpartum, with risk estimates ranging from 1.27-1.54. Investigators in Scotland found psychiatric admissions fell during pregnancy and increased in the early postpartum period, particularly during the first two weeks postpartum; they remained elevated up to two years after delivery compared to pre-pregnancy rates (40). A New York State study found increasing rates of hospitalizations for depression in the first year after delivery from 1995-2004 (41). In a meta-analysis, the strongest predictors for postpartum depression included depression during pregnancy and a previous history of depression (42).

Maternal hypertensive disorders, severe maternal morbidity and rehospitalization

Both hypertensive disorders and SMM at delivery increased the risk of rehospitalization within the first year postpartum. In our analysis, 1.0% of women without SMM at delivery and without maternal hypertensive disorders had an HD rehospitalization in the first year; rehospitalization ranged for women with either a maternal hypertensive disorder or SMM at delivery between 2.2 and 8.9% in the first year.

When assessed together, the independent association of SMM on rehospitalization appeared greater than that of maternal hypertensive disorders. Compared to deliveries to women without SMM and without any hypertensive disorders, the risk of HD rehospitalization within six weeks and one year was greater for deliveries to women with SMM than those with hypertensive disorders. Having both SMM and any type of

hypertensive disorder increased the risk of HD rehospitalization to more than 3-fold within six weeks and more than 2-fold within one year. When aggregated by pre-existing chronic medical conditions, conditions occurring in pregnancy, and SMM at delivery, the risk of HD rehospitalization was not attenuated for deliveries to women with pre-existing conditions up to one year postpartum, highlighting the continued adverse effects of these conditions.

Our research aligns with the conceptual framework that integrates the life course perspective in health outcomes and incorporates both critical and sensitive periods and a cumulative pathways model over time (43). Both hypertensive disorders and SMM at delivery together increased the risk of HD rehospitalization above the presence of any hypertensive disorder alone. However, the number of SMM indicators did not increase rehospitalization risk; rather, the presence of at least one SMM indicator at delivery was a critical factor in increased rehospitalization risk.

Previous studies on postpartum rehospitalization have seldom included both pre-existing conditions and delivery events. Liu et al. (2005) observed an almost doubling of odds of 60 day rehospitalization among Canadian women with cesarean compared to spontaneous vaginal delivery (23). In Aim 3, the risk of HD rehospitalization within six weeks was 30% greater in women with cesarean delivery compared to vaginal delivery, significantly less than the risk of SMM at delivery or any type of maternal hypertensive disorder. While method of delivery may have been a proxy for severe events at delivery in previous studies, the current study adds greater specificity to understanding the impact of hypertensive disorders and severe events at delivery on postpartum maternal health.

Our study results also are consistent with research about intermediate and longer-term adverse outcomes in women, adding to our understanding of chronic disease across the life course. In a Dutch case control study, markers of future maternal cardiovascular disease a median of 7.1 years after delivery were significantly higher among women with a history of preeclampsia than those without; these markers included fasting glucose levels, larger waist circumferences, and hypertension (44). In a study of Kentucky women 50 years and older, women with one or more pregnancy complication (preterm labor, preeclampsia, gestational diabetes, and third trimester bleeding) had increased odds of cardiovascular disease (including: angina, heart attack, heart failure, arrhythmia) compared to women who were never pregnant; women who were pregnant with no pregnancy complications had similar risks of cardiovascular disease compared to women who were never pregnant (45). The current study identified adverse outcomes among postpartum women with hypertensive disorders and severe events at delivery, although for a shorter term.

SMM appeared to slightly moderate the relation between some types hypertensive disorders and rehospitalization, although the effect was not strong. In particular, SMM appeared to moderate the impact of more severe types of hypertension, including superimposed and severe preeclampsia, on HD and OS rehospitalizations as evaluated by significant interaction terms. When SMM was not present, there was an increased risk of HD and OS rehospitalization for deliveries to women with superimposed and severe preeclampsia compared to those to women without hypertensive disorders versus when SMM was present. SMM did not appear to mediate the relation between hypertensive disorders and any type of rehospitalization. Previous researchers have suggested

pregnancy complications may predict later chronic disease, including cardiovascular disease (46). The results from Aim 3 support strong independent effects of both SMM at delivery and hypertensive disorders on rehospitalization risk in the first six weeks and year postpartum.

Study Strengths

The linkage of vital records with hospital discharge data in our study allowed for fuller investigation of variables to study the relation of chronic and pregnancy-associated conditions, SMM at delivery and rehospitalization. This linkage enabled better ascertainment of key variables including chronic and gestational hypertension as well as pre-existing and gestational diabetes, compared to each data source alone (47, 48). In addition, other potential confounding social and biological variables from the birth certificate and fetal death record were included in the analyses, reducing potential residual confounding.

Another strength was that multiple deliveries across the same women were included during the study period, using a generalized estimating equations approach; this approach provided better error estimates of the parameters of association.
Our population-level approach in Aims 1 and 3 was representative of deliveries to all resident women in MA hospitals, and may be generalizable of deliveries to women in the US with similar characteristics to MA. The more than half a million delivery records provided increased statistical power to differentiate maternal hypertensive disorders, specifically superimposed preeclampsia.

Another strength of our study was our ability to use linked data to examine maternal morbidity at delivery and into the postpartum period in Aims 2 and 3. This

approach limited temporal ambiguity as the exposure and outcome variables were obtained from different sources at different points in time.

Study Limitations

The use of hospital discharge data enabled a population-level approach but also had several limitations. The hospital discharge database is primarily an administrative database with the main purpose of billing; these data may more accurately reflect conditions that affect reimbursement. Obstetric diagnoses usually do not impact reimbursement, and may not be abstracted as carefully as medical-surgical conditions (49). There is a potential for underestimation of maternal comorbidities in hospital discharge data since coding standards only require coding of conditions that affect the current condition (50). With a high specificity and lowered sensitivity (2), this underestimation more likely influenced ascertainment of preexisting conditions that are not also documented on the birth certificate. The birth certificate also has noted low sensitivities on pre-existing maternal conditions; however, when these data are combined with the hospital discharge data, ascertainment more closely reflects data from the medical record (48).

We did not have access to outpatient data, and relied on rehospitalization information as a way to understand maternal morbidity in the postpartum period. There is the potential that sick women may be seen in outpatient rather than hospital settings, particularly ED admissions, although the sickest, who were captured in our study, were still likely to be seen in the hospital.

Previous studies have suggested that the association of hypertensive disorders with cardiovascular risk may be largely due to shared pre-pregnancy risk factors, such as

obesity and blood pressure (51). While we focused on many pre-pregnancy conditions, our study had limited obesity information from the hospital discharge at delivery and only post-2011 obesity data on the birth certificate; this information could not be used in the analysis. There were other unmeasured variables that are common risk factors that were not be included in the study, such as the family history of disease.

Public Health Implications

Overall, this research furthers our knowledge of the continuum of maternal health in the US from pre-pregnancy through the first year postpartum. Our research suggests that women with both maternal hypertensive disorders and SMM at delivery are at increased risk of adverse events that extend beyond the delivery hospitalization into both the first six weeks and one year postpartum. The need to draw attention to this small, but perhaps growing number of women, at the time of postpartum discharge is highlighted by our findings. Public health implications of this research include primary and secondary prevention of hypertensive disorders, prevention of SMM, as well as mitigation of the consequences of both hypertensive disorders and SMM postpartum.

Prevention strategies for hypertensive disorders during pregnancy may be focused on more distal determinants of maternal health, including the physical and social environment, and women's underlying health before pregnancy (52). More proximate primary strategies, such as the supplementation of calcium and vitamins C and E have not been shown to be effective in randomized controlled trials (53, 54), while other strategies for prevention of preeclampsia have been implemented in recent years. For example, the United States Preventive Task Force (USPTF) updated clinical guidelines in 2014 to prescribe low dose aspirin (81mg/d) after 12 weeks gestation to asymptomatic pregnant

women at high risk for preeclampsia; here, the USPTF defined high risk as either: a history of preeclampsia, multifetal gestation, chronic hypertension, type 1 or 2 diabetes, or renal disease and autoimmune disease.

Further, there are antihypertensive medication recommendations for pregnant women. Randomized controlled trials have shown the benefit of magnesium sulfate prophylaxsis to prevent seizures in preeclamptic women (55-57). In a systematic review of 15 trials, magnesium sulfate was shown to more than halve the risk of eclampsia and potentially reduce maternal death with limited side effects (58). A focus of the subtypes of hypertensive disorders in pregnancy at a population-based level in this research has the potential to inform these prevention and management strategies.

At the state level, Perinatal Quality Collaboratives (PQCs) are one mechanism to address hypertensive disorders, SMM and postpartum maternal health. According to the CDC, state PQCs are "networks of perinatal care providers and public health professionals working to improve pregnancy outcomes for women and newborns by advancing evidence-based clinical practices and processes through continuous quality improvement (CQI)" (59). Successful PQC projects in California and New York have been found to decrease the percentage of non-medically indicated deliveries between 37 and 38 weeks gestation through a variety of interventions including: improving patient and provider education, encouraging use of optimal gestational dating criteria, and improving communication (59). The use of PQCs to successfully reduce hypertension and severe maternal morbidity at delivery is still unclear.

At the both the state and facility level, one strategy for prevention of SMM is implementing Quality Improvement projects created by the National Partnership for

Maternal Safety, a national initiative for every birthing center in the US to have a safety program in place for the most common preventable causes of maternal morbidity and death (60). In 2012, the National Partnership for Maternal Safety identified the need for development of three maternal safety bundles for 1) obstetric hemorrhage, 2) severe hypertension, and 3) venous thromboembolism. A safety bundle includes a set of evidence-based practices that have been shown to improve patient outcomes covering the domains of readiness, recognition and prevention, response, and reporting/systems learning. The hypertension safety bundle was developed in May 2015 (61).

Also at the facility level, the CDC and the American College of Obstetricians and Gynecologists (ACOG) have recently called for a facility-based identification of women with severe maternal morbidity (62, 63). Although there is not complete consensus among systems and professional organizations about the conditions that represent severe maternal morbidity, they recommend operational criteria for surveillance and review to include 1) women who receive transfusion greater than or equal to 4 units of blood or 2) are admitted to the Intensive Care Unit. The goal of the reviews is to focus on the prevention of morbidity and identify whether there were opportunities to alter the outcome (strong, possible, none). If there were strong or possible opportunities to do so, the review committee makes specific recommendations.

Geller et al. (2004) proposed that preventability of severe morbidity and death occurs at three levels: the overall system (communication, policies and procedures, and care process), overall provider (failure to identify high-risk status, incomplete or inappropriate management, or no referral to a tertiary care facility), and overall patient (non-adherence) levels (64). Researchers examined cases of pregnant or recently

postpartum women admitted to the Intensive Care Unit in New Zealand who experienced severe acute maternal morbidity and found that more than one third of cases were potentially preventable (65). Among preventable factors, clinician-related factors included a failure to diagnosis or recognize high-risk status and a delay in treatment or inappropriate treatment; the most common causes of preventable severe morbidity were blood loss and septicemia (65). Specific to cardiovascular morbidity, researchers suggest the importance of the obstetrician to identify risk factors during pregnancy to enhance prevention efforts, as pregnancy provides a critical time to influence risk factors (66).

Mitigating the consequences of SMM after delivery may involve more comprehensive discharge planning at delivery hospitalization. The number of women with SMM is relatively small, indicating that attention to the needs of these women would be highly feasible. The best strategies for addressing the needs of these women, however, remain unclear. Research findings evaluating discharge readiness, which addressed a more individualized approach through taking into consideration the opinions of the mother, pediatrician and obstetrician for the timing of discharge, noted increased health care use and poorer health outcomes 2-4 weeks post-delivery among mother-infant dyads when there was discordance in opinions about discharge readiness (67). A systematic review of randomized controlled trials of universal postpartum home visits by trained individuals or health care professionals did not show significant improvements in outcomes of: maternal knowledge, attitudes, parenting skills, mental health, quality of life, or physical health (68, 69); however, home visits may improve maternal satisfaction with postpartum support and reduce postpartum depression scores among women at high risk for family dysfunction or postpartum depression.

The prevention, early diagnosis, and management of maternal hypertensive disorders may benefit not only the mother but the infant as well. Poor infant outcomes are directly related to preeclampsia as well as to prematurity that results from appropriate induction of delivery of women with preeclampsia. Preeclampsia is estimated to account for 15% of preterm births in the United States and almost one quarter of medically indicated preterm births are indicated for preeclampsia (70, 71). Early onset preeclampsia was associated with almost a six-fold increase in odds of fetal death and sixteen fold increase in odds of perinatal death or severe neonatal morbidity; late onset preeclampsia was associated with a two-fold increase in odds of perinatal death or severe neonatal morbidity among women with singleton births in Washington State between 2000 and 2008 (72). In a recent retrospective cohort study of all deliveries in 16 California hospitals, Kilpatrick et al. (2016) found 43% of women with severe maternal morbidity delivered preterm with 8% delivering <32 weeks (73). The importance of addressing maternal hypertensive disorders and severe maternal morbidity is critical for maternal health but also extends beyond it.

Conclusions

This research addressed a key gap in maternal health research and added to the literature on the continuum of maternal health before, during and after delivery. Hypertensive disorders and other chronic and pregnancy-associated conditions increased the odds of severe maternal morbidity at delivery and the risk of rehospitalization in the first six weeks and one year postpartum. The study results also showed severe events at delivery independently increased the risk of rehospitalization within the first year postpartum. Although the number of women with severe events at delivery is small, it is a

growing population warranting additional research. Our study highlights the need for efforts to prevent and manage hypertensive disorders and other chronic and pregnancy-associated conditions before, during, and after pregnancy as well as the need to address preventable severe maternal morbidity and mitigate its impacts after delivery through the first year postpartum. These latter findings on rehospitalization warrant additional research to determine if they prevail in other populations or settings.

References

1. Berg CJ, Mackay AP, Qin C, Callaghan WM. Overview of maternal morbidity during hospitalization for labor and delivery in the United States: 1993-1997 and 2001-2005. Obstet Gynecol. 2009;113(5):1075-81. Epub 2009/04/23.

2. Fridman M, Korst LM, Chow J, Lawton E, Mitchell C, Gregory KD. Trends in maternal morbidity before and during pregnancy in California. Am J Public Health. 2014;104 Suppl 1:S49-57. Epub 2013/12/21.

3. Kuklina EV, Ayala C, Callaghan WM. Hypertensive disorders and severe obstetric morbidity in the United States. Obstet Gynecol. 2009;113(6):1299-306. Epub 2009/05/23.

4. Roberts CL, Ford JB, Algert CS, Antonsen S, Chalmers J, Cnattingius S, et al. Population-based trends in pregnancy hypertension and pre-eclampsia: an international comparative study. BMJ Open. 2011;1(1):e000101. Epub 2011/10/25.

5. Savitz DA, Danilack VA, Engel SM, Elston B, Lipkind HS. Descriptive epidemiology of chronic hypertension, gestational hypertension, and preeclampsia in New York State, 1995-2004. Matern Child Health J. 2014;18(4):829-38. Epub 2013/06/25.

6. Callaghan WM, Creanga AA, Kuklina EV. Severe maternal morbidity among delivery and postpartum hospitalizations in the United States. Obstet Gynecol. 2012;120(5):1029-36. Epub 2012/10/24.

7. Kilpatrick SJ, Abreo A, Greene N, Melsop K, Peterson N, Shields LE, et al. Severe maternal morbidity in a large cohort of women with acute severe intrapartum hypertension. Am J Obstet Gynecol. 2016;215(1):91 e1-7. Epub 2016/02/02.

8. Madazli R, Yuksel MA, Imamoglu M, Tuten A, Oncul M, Aydin B, et al. Comparison of clinical and perinatal outcomes in early- and late-onset preeclampsia. Arch Gynecol Obstet. 2014;290(1):53-7. Epub 2014/02/20.

9. Steegers EA, von Dadelszen P, Duvekot JJ, Pijnenborg R. Pre-eclampsia. Lancet. 2010;376(9741):631-44. Epub 2010/07/06.

10. Roberts JM, Pearson G, Cutler J, Lindheimer M. Summary of the NHLBI Working Group on Research on Hypertension During Pregnancy. Hypertension. 2003;41(3):437-45. Epub 2003/03/08.

11. Conde-Agudelo A, Romero R. Amniotic fluid embolism: an evidence-based review. Am J Obstet Gynecol. 2009;201(5):445 e1-13. Epub 2009/11/03.

12. Wang G, Murphy VE, Namazy J, Powell H, Schatz M, Chambers C, et al. The risk of maternal and placental complications in pregnant women with asthma: a systematic review and meta-analysis. J Matern Fetal Neonatal Med. 2014;27(9):934-42. Epub 2013/10/12.

13. Wahabi HA, Esmaeil SA, Fayed A, Al-Shaikh G, Alzeidan RA. Pre-existing diabetes mellitus and adverse pregnancy outcomes. BMC Res Notes. 2012;5:496. Epub 2012/09/12.

14. Borchers AT, Naguwa SM, Keen CL, Gershwin ME. The implications of autoimmunity and pregnancy. J Autoimmun. 2010;34(3):J287-99. Epub 2009/12/25.

15. Maeda A, Bateman BT, Clancy CR, Creanga AA, Leffert LR. Opioid abuse and dependence during pregnancy: temporal trends and obstetrical outcomes. Anesthesiology. 2014;121(6):1158-65. Epub 2014/11/19.

16. Palmsten K, Huybrechts KF, Michels KB, Williams PL, Mogun H, Setoguchi S, et al. Antidepressant use and risk for preeclampsia. Epidemiology. 2013;24(5):682-91. Epub 2013/07/23.

17. Hartling L, Dryden DM, Guthrie A, Muise M, Vandermeer B, Donovan L. Diagnostic thresholds for gestational diabetes and their impact on pregnancy outcomes: a systematic review. Diabet Med. 2014;31(3):319-31. Epub 2014/02/18.

18. Gray KE, Wallace ER, Nelson KR, Reed SD, Schiff MA. Population-based study of risk factors for severe maternal morbidity. Paediatr Perinat Epidemiol. 2012;26(6):506-14. Epub 2012/10/16.

19. Lyndon A, Lee HC, Gilbert WM, Gould JB, Lee KA. Maternal morbidity during childbirth hospitalization in California. J Matern Fetal Neonatal Med. 2012;25(12):2529-35. Epub 2012/07/12.

20. Engel SM, Janevic TM, Stein CR, Savitz DA. Maternal smoking, preeclampsia, and infant health outcomes in New York City, 1995-2003. Am J Epidemiol. 2009;169(1):33-40. Epub 2008/11/13.

21. Howell EA, Egorova N, Balbierz A, Zeitlin J, Hebert PL. Black-white differences in severe maternal morbidity and site of care. Am J Obstet Gynecol. 2016;214(1):122 e1-7. Epub 2015/08/19.

22. Belfort MA, Clark SL, Saade GR, Kleja K, Dildy GA, 3rd, Van Veen TR, et al. Hospital readmission after delivery: evidence for an increased incidence of nonurogenital infection in the immediate postpartum period. Am J Obstet Gynecol. 2010;202(1):35 e1-7. Epub 2009/11/06.

23. Liu S, Heaman M, Kramer MS, Demissie K, Wen SW, Marcoux S. Length of hospital stay, obstetric conditions at childbirth, and maternal readmission: a population-based cohort study. Am J Obstet Gynecol. 2002;187(3):681-7. Epub 2002/09/19.

24. Lydon-Rochelle M, Holt VL, Martin DP, Easterling TR. Association between method of delivery and maternal rehospitalization. JAMA. 2000;283(18):2411-6. Epub 2000/05/18.

25. Cox S, Dean T, Posner SF, Jamieson DJ, Curtis KM, Johnson CH, et al. Disparities in reproductive health-related visits to the emergency department in Maryland by age and race, 1999-2005. J Womens Health (Larchmt). 2011;20(12):1833-8. Epub 2011/11/15.

26. Declercq E, Barger M, Cabral HJ, Evans SR, Kotelchuck M, Simon C, et al. Maternal outcomes associated with planned primary cesarean births compared with planned vaginal births. Obstet Gynecol. 2007;109(3):669-77. Epub 2007/03/03.

27. Sharvit M, Rubinstein T, Ravid D, Shechter-Maor G, Fishman A, Biron-Shental T. Patients with high-risk pregnancies and complicated deliveries have an increased risk of maternal postpartum readmissions. Arch Gynecol Obstet. 2014;290(4):629-33. Epub 2014/05/08.

28. Sutton JP, Friedman B. Trends in Septicemia Hospitalizations and Readmissions in Selected HCUP States, 2005 and 2010: Statistical Brief #161. Healthcare Cost and Utilization Project (HCUP) Statistical Briefs. Rockville (MD)2006.

29. Hemsell DL. Infection after hysterectomy. Infect Dis Obstet Gynecol. 1997;5(1):52-6. Epub 1997/01/01.

30. Savitz DA, Danilack VA, Elston B, Lipkind HS. Pregnancy-induced hypertension and diabetes and the risk of cardiovascular disease, stroke, and diabetes hospitalization in the year following delivery. Am J Epidemiol. 2014;180(1):41-4. Epub 2014/06/01.

31. Hamilton MS, Brooten D, Youngblut JM. High-risk pregnancy: postpartum rehospitalization. J Perinatol. 2002;22(7):566-71. Epub 2002/10/09.

32. Harris A, Chang HY, Wang L, Sylvia M, Neale D, Levine D, et al. Emergency Room Utilization After Medically Complicated Pregnancies: A Medicaid Claims Analysis. J Womens Health (Larchmt). 2015;24(9):745-54. Epub 2015/08/01.

33. Metzger BE, Buchanan TA, Coustan DR, de Leiva A, Dunger DB, Hadden DR, et al. Summary and recommendations of the Fifth International Workshop-Conference on Gestational Diabetes Mellitus. Diabetes Care. 2007;30 Suppl 2:S251-60. Epub 2008/02/27.

34. Shah BR, Retnakaran R, Booth GL. Increased risk of cardiovascular disease in young women following gestational diabetes mellitus. Diabetes Care. 2008;31(8):1668-9. Epub 2008/05/20.

35. Clifton VL, Giles WB, Smith R, Bisits AT, Hempenstall PA, Kessell CG, et al. Alterations of placental vascular function in asthmatic pregnancies. Am J Respir Crit Care Med. 2001;164(4):546-53. Epub 2001/08/25.

36. Buyon JP. The effects of pregnancy on autoimmune diseases. J Leukoc Biol. 1998;63(3):281-7. Epub 1998/03/21.

37. Confavreux C, Hutchinson M, Hours MM, Cortinovis-Tourniaire P, Moreau T. Rate of pregnancy-related relapse in multiple sclerosis. Pregnancy in Multiple Sclerosis Group. N Engl J Med. 1998;339(5):285-91. Epub 1998/07/31.

38. Silman A, Kay A, Brennan P. Timing of pregnancy in relation to the onset of rheumatoid arthritis. Arthritis Rheum. 1992;35(2):152-5. Epub 1992/02/01.

39. Ebrahim SH, Gfroerer J. Pregnancy-related substance use in the United States during 1996-1998. Obstet Gynecol. 2003;101(2):374-9. Epub 2003/02/11.

40. Langan Martin J, McLean G, Cantwell R, Smith DJ. Admission to psychiatric hospital in the early and late postpartum periods: Scottish national linkage study. BMJ Open. 2016;6(1):e008758. Epub 2016/01/07.

41. Savitz DA, Stein CR, Ye F, Kellerman L, Silverman M. The epidemiology of hospitalized postpartum depression in New York State, 1995-2004. Ann Epidemiol. 2011;21(6):399-406. Epub 2011/05/10.

42. Robertson E, Grace S, Wallington T, Stewart DE. Antenatal risk factors for postpartum depression: a synthesis of recent literature. Gen Hosp Psychiatry. 2004;26(4):289-95. Epub 2004/07/06.

43. Lu MC, Halfon N. Racial and ethnic disparities in birth outcomes: a life-course perspective. Matern Child Health J. 2003;7(1):13-30. Epub 2003/04/25.

44. Berends AL, de Groot CJ, Sijbrands EJ, Sie MP, Benneheij SH, Pal R, et al. Shared constitutional risks for maternal vascular-related pregnancy complications and future cardiovascular disease. Hypertension. 2008;51(4):1034-41. Epub 2008/02/09.

45. Freibert SM, Mannino DM, Bush H, Crofford LJ. The association of adverse pregnancy events and cardiovascular disease in women 50 years of age and older. J Womens Health (Larchmt). 2011;20(2):287-93. Epub 2011/01/27.

46. Rich-Edwards JW, McElrath TF, Karumanchi SA, Seely EW. Breathing life into the lifecourse approach: pregnancy history and cardiovascular disease in women. Hypertension. 2010;56(3):331-4. Epub 2010/08/04.

47. Lain SJ, Hadfield RM, Raynes-Greenow CH, Ford JB, Mealing NM, Algert CS, et al. Quality of data in perinatal population health databases: a systematic review. Med Care. 2012;50(4):e7-20. Epub 2011/05/28.

48. Lydon-Rochelle MT, Holt VL, Cardenas V, Nelson JC, Easterling TR, Gardella C, et al. The reporting of pre-existing maternal medical conditions and complications of pregnancy on birth certificates and in hospital discharge data. Am J Obstet Gynecol. 2005;193(1):125-34. Epub 2005/07/16.

49. Yasmeen S, Romano PS, Schembri ME, Keyzer JM, Gilbert WM. Accuracy of obstetric diagnoses and procedures in hospital discharge data. Am J Obstet Gynecol. 2006;194(4):992-1001. Epub 2006/04/04.

50. Hart AS, MS; Ford, B, editor. ICD-9-CM Expert for Hospitals 6th ed. Salt Lake City, UT: Ingenix; 2010.

51. Romundstad PR, Magnussen EB, Smith GD, Vatten LJ. Hypertension in pregnancy and later cardiovascular risk: common antecedents? Circulation. 2010;122(6):579-84. Epub 2010/07/28.

52. Misra DP, Guyer B, Allston A. Integrated perinatal health framework. A multiple determinants model with a life span approach. Am J Prev Med. 2003;25(1):65-75. Epub 2003/06/24.

53. Sibai BM. Hypertensive disorders of pregnancy: the United States perspective. Curr Opin Obstet Gynecol. 2008;20(2):102-6. Epub 2008/04/05.

54. Roberts JM, Myatt L, Spong CY, Thom EA, Hauth JC, Leveno KJ, et al. Vitamins C and E to prevent complications of pregnancy-associated hypertension. N Engl J Med. 2010;362(14):1282-91. Epub 2010/04/09.

55. Altman D, Carroli G, Duley L, Farrell B, Moodley J, Neilson J, et al. Do women with pre-eclampsia, and their babies, benefit from magnesium sulphate? The Magpie Trial: a randomised placebo-controlled trial. Lancet. 2002;359(9321):1877-90. Epub 2002/06/12.

56. Belfort MA, Anthony J, Saade GR, Allen JC, Jr. A comparison of magnesium sulfate and nimodipine for the prevention of eclampsia. N Engl J Med. 2003;348(4):304-11. Epub 2003/01/24.

57. Lucas MJ, Leveno KJ, Cunningham FG. A comparison of magnesium sulfate with phenytoin for the prevention of eclampsia. N Engl J Med. 1995;333(4):201-5. Epub 1995/07/27.

58. Duley L, Gulmezoglu AM, Henderson-Smart DJ, Chou D. Magnesium sulphate and other anticonvulsants for women with pre-eclampsia. Cochrane Database Syst Rev. 2010(11):CD000025. Epub 2010/11/12.

59. Henderson ZT, Suchdev DB, Abe K, Johnston EO, Callaghan WM. Perinatal quality collaboratives: improving care for mothers and infants. J Womens Health (Larchmt). 2014;23(5):368-72. Epub 2014/03/25.

60. D'Alton ME, Main EK, Menard MK, Levy BS. The National Partnership for Maternal Safety. Obstet Gynecol. 2014;123(5):973-7. Epub 2014/05/03.

61. Patient Safety Bundle: Hypertension. 2015.

62. Callaghan WM, Grobman WA, Kilpatrick SJ, Main EK, D'Alton M. Facility-based identification of women with severe maternal morbidity: it is time to start. Obstet Gynecol. 2014;123(5):978-81. Epub 2014/05/03.

63. Obstetric Care Consensus No 5 Summary: Severe Maternal Morbidity: Screening And Review. Obstet Gynecol. 2016;128(3):670-1. Epub 2016/08/23.

64. Geller SE, Rosenberg D, Cox SM, Brown ML, Simonson L, Driscoll CA, et al. The continuum of maternal morbidity and mortality: factors associated with severity. Am J Obstet Gynecol. 2004;191(3):939-44. Epub 2004/10/07.

65. Lawton B, MacDonald EJ, Brown SA, Wilson L, Stanley J, Tait JD, et al. Preventability of severe acute maternal morbidity. Am J Obstet Gynecol. 2014;210(6):557 e1-6. Epub 2014/02/11.

66. Ehrenthal DB, Catov JM. Importance of engaging obstetrician/gynecologists in cardiovascular disease prevention. Curr Opin Cardiol. 2013;28(5):547-53. Epub 2013/08/10.

67. Bernstein HH, Spino C, Lalama CM, Finch SA, Wasserman RC, McCormick MC. Unreadiness for postpartum discharge following healthy term pregnancy: impact on health care use and outcomes. Acad Pediatr. 2013;13(1):27-39. Epub 2012/10/27.

68. Shaw E, Levitt C, Wong S, Kaczorowski J. Systematic review of the literature on postpartum care: effectiveness of postpartum support to improve maternal parenting, mental health, quality of life, and physical health. Birth. 2006;33(3):210-20. Epub 2006/09/05.

69. Yonemoto N, Dowswell T, Nagai S, Mori R. Schedules for home visits in the early postpartum period. Cochrane Database Syst Rev. 2013;7:CD009326. Epub 2013/07/25.

70. Henderson JT, Whitlock EP, O'Connor E, Senger CA, Thompson JH, Rowland MG. Low-dose aspirin for prevention of morbidity and mortality from preeclampsia: a systematic evidence review for the U.S. Preventive Services Task Force. Ann Intern Med. 2014;160(10):695-703. Epub 2014/04/09.

71. Ananth CV, Vintzileos AM. Epidemiology of preterm birth and its clinical subtypes. J Matern Fetal Neonatal Med. 2006;19(12):773-82. Epub 2006/12/28.

72. Lisonkova S, Sabr Y, Mayer C, Young C, Skoll A, Joseph KS. Maternal morbidity associated with early-onset and late-onset preeclampsia. Obstet Gynecol. 2014;124(4):771-81. Epub 2014/09/10.

73. Kilpatrick SJ, Abreo A, Gould J, Greene N, Main EK. Confirmed severe maternal morbidity is associated with high rate of preterm delivery. Am J Obstet Gynecol. 2016;215(2):233 e1-7. Epub 2016/02/24.

Appendix A

Adjusted Relative Risk of Rehospitalization by Social and Biological Characteristics, Deliveries to MA Women 2002-2011

Aim 3 Multivariate Models
Adjusted Relative Risk of 6 weeks Hospital Rehospitalizations by Social and Biological Characteristics, Deliveries to MA Women 2002-2011

Characteristic	aRR Hospital Discharge Rehospitalization[1]	aRR Observational Stay Rehospitalization[1]	aRR Emergency Department Rehospitalization[1]
Age			
<20	**1.19 (1.07-1.31)**	1.18 (0.97-1.43)	**1.28 (1.22-1.34)**
20-24	**1.09 (1.01-1.17)**	**1.16 (1.01-1.33)**	**1.17 (1.13-1.21)**
25-29	REF	REF	REF
30-34	**1.07 (1.01-1.14)**	1.10 (0.98-1.23)	**0.87 (0.85-0.91)**
35-39	**1.10 (1.03-1.18)**	**1.25 (1.10-1.41)**	**0.83 (0.79-0.86)**
40+	**1.28 (1.16-1.42)**	**1.26 (1.04-1.51)**	**0.83 (0.78-0.89)**
Race/ethnicity			
Hispanic	**1.10 (1.02-1.18)**	0.93 (0.81-1.06)	0.91 (0.98-1.07)
Non-Hispanic White	REF	REF	REF
Non-Hispanic Black	**1.46 (1.36-1.56)**	**1.20 (1.05-1.37)**	1.02 (0.98-1.07)
Non-Hispanic Asian	0.89 (0.81-0.97)	0.82 (0.69-0.97)	**0.59 (0.64-0.73)**
Other	1.08 (0.93-1.25)	0.94 (0.70-1.24)	0.98 (0.91-1.06)
Education			
<HS	**0.90 (0.84-0.97)**	1.06 (0.92-1.22)	1.02 (0.99-1.06)
HS/GED	REF	REF	REF
Some college	0.93 (0.86-1.01)	1.14(0.996-1.30)	**0.88 (0.85-0.92)**
Bachelors +	**0.87 (0.82-0.93)**	0.90 (0.81-1.00)	**0.70 (0.67-0.72)**
Insurance Payer			
Private	REF	REF	REF
Public	**1.23 (1.16-1.31)**	0.99 (0.88-1.10)	**1.65 (1.60-1.71)**
Self-pay	**1.23 (1.01-1.49)**	1.01 (0.70-1.48)	0.95 (0.81-1.11)
Free care	1.07 (0.85-1.35)	0.61 (0.36-1.03)	**1.27 (1.11-1.44)**
Marital Status			
Married	1.04 (0.98-1.10)	1.04 (0.92-1.16)	0.91(0.88-0.93)
Not married	REF	REF	REF
Cigarette use in pregnancy			
Yes	**1.20 (1.11-1.31)**	**1.20 (1.04-1.40)**	**1.42 (1.37-1.47)**
No	REF	REF	REF
Parity			
1	REF	REF	REF
2	**0.93 (0.88-0.98)**	0.94 (0.85-1.05)	0.97 (0.94-1.00)
3+	1.00 (0.94-1.07)	1.01 (0.90-1.14)	**1.05 (1.02-1.09)**
Plurality			
Singletons	REF	REF	REF
Twins	**1.47 (1.33-1.63)**	0.97 (0.77-1.21)	1.05 (0.97-1.14)
Triplets +	**1.68 (1.10-2.55)**	**2.28 (1.14-4.58)**	1.41 (0.94-2.13)
Method of Delivery			
Vaginal	REF	REF	REF
VBAC	1.05 (0.89-1.23)	1.18 (0.90-1.54)	1.04 (0.95-1.13)
Primary Cesarean	**1.30 (1.22-1.38)**	1.08 (0.96-1.21)	**1.24 (1.19-1.28)**
Repeat Cesarean	**1.11 (1.03-1.19)**	1.13 (0.99-1.29)	**1.29 (1.24-1.34)**
Hospital Level			

1	**0.79 (0.74-0.84)**	1.09 (0.98-1.21)	**1.58 (1.53-1.63)**
2	**0.91 (0.86-0.95)**	0.95 (0.85-1.05)	**1.44 (1.40-1.48)**
3	REF	REF	REF
Length of Stay at delivery			
1-2 days	REF	REF	REF
3-4 days	**1.40 (1.32-1.48)**	**1.32 (1.19-1.46)**	**1.17 (1.13-1.20)**
5+ days	**1.83 (1.68-1.99)**	**1.54 (1.31-1.80)**	**1.31 (1.25-1.38)**
Delivery Year			
2002-2003	REF	REF	REF
2004-2005	0.97 (0.91-1.03)	0.92 (0.81-1.03)	1.00 (0.97-1.04)
2006-2007	1.00 (0.94-1.07)	0.98 (0.87-1.10)	**1.10 (1.06-1.14)**
2008-2009	0.97 (0.91-1.03)	0.92 (0.81-1.04)	**1.13 (1.09-1.17)**
2010-2011	0.98 (0.92-1.05)	0.98 (0.87-1.11)	**1.13 (1.09-1.17)**

[1]Also adjusted for SMM, maternal hypertensive disorders, pre-existing and gestational diabetes, asthma, autoimmune conditions
Bold: p<0.05

Adjusted Relative Risk of 1 Year Hospital Rehospitalizations by Social and Biological Characteristics, Deliveries to MA Women 2002-2011

Characteristic	aRR HD[1]	aRR OS[1]	aRR ED[1]
Age			
<20	**1.18 (1.11-1.26)**	**1.34 (1.21-1.49)**	**1.47 (1.44-1.49)**
20-24	**1.08 (1.03-1.13)**	**1.14 (1.06-1.22)**	**1.25 (1.23-1.27)**
25-29	REF	REF	REF
30-34	1.01 (0.97-1.05)	0.98 (0.92-1.04)	**0.83 (0.81-0.94)**
35-39	1.01 (0.97-1.06)	1.01 (0.93-1.08)	**0.73 (0.72-0.74)**
40+	**1.15 (1.07-1.23)**	1.06 (0.95-1.19)	**0.70 (0.68-0.73)**
Race/ethnicity			
Hispanic	**0.93 (0.89-0.97)**	**0.92 (0.86-0.99)**	**0.92 (0.90-0.93)**
Non-Hispanic White	REF	REF	REF
Non-Hispanic Black	**1.12 (1.07-1.23)**	1.08 (1.00-1.17)	**1.12 (1.11-1.14)**
Non-Hispanic Asian	**0.68 (0.63-0.72)**	**0.59 (0.52-0.66)**	**0.56 (0.54-0.57)**
Other	0.96 (0.88-1.05)	**0.92 (0.79-1.08)**	1.03 (0.995-1.06)
Education			
<HS	0.96 (0.92-1.00)	0.96 (0.89-1.04)	**0.97 (0.96-0.99)**
HS/GED	REF	REF	REF
Some college	0.98 (0.94-1.03)	1.05 (0.97-1.13)	**0.93 (0.91-0.95)**
Bachelors +	**0.78 (0.75-0.82)**	**0.79 (0.74-0.85)**	**0.68 (0.67-0.69)**
Insurance Payer			
Private	REF	REF	REF
Public	**1.24 (1.20-1.29)**	1.02 (0.96-1.09)	**1.48 (1.46-1.50)**
Self-pay	1.06 (0.92-1.21)	1.04 (0.83-1.31)	0.97 (0.91-1.04)
Free care	**1.20 (1.04-1.39)**	0.85 (0.66-1.11)	**1.23 (1.26-1.30)**
Marital Status			
Married	**0.91 (0.88-0.94)**	**0.89 (0.84-0.95)**	**0.81 (0.80-0.82)**
Not married	REF	REF	REF
Cigarette use in pregnancy			
Yes	**1.37 (1.31-1.43)**	**1.25 (1.16-1.35)**	**1.36 (1.34-1.38)**
No	REF	REF	REF
Parity			
1	REF	REF	REF
2	**1.08 (1.05-1.12)**	**1.17 (1.10-1.24)**	**1.10 (1.09-1.11)**
3+	**1.21 (1.16-1.26)**	**1.29 (1.20-1.38)**	**1.23 (1.21-1.25)**
Plurality			

Singletons	REF	REF	REF
Twins	**1.22 (1.13-1.32)**	1.05 (0.91-1.20)	**0.94 (0.91-0.98)**
Triplets +	1.36 (0.97-1.90)	1.38 (0.78-2.41)	1.18 (0.96-1.44)
Method of Delivery			
Vaginal	REF	REF	REF
VBAC	0.94 (0.85-1.04)	0.98 (0.84-1.15)	**0.96 (0.93-0.999)**
Primary Cesarean	**1.13 (1.08-1.18)**	1.02 (0.95-1.10)	**1.07 (1.05-1.08)**
Repeat Cesarean	**1.07 (1.02-1.12)**	1.07 (0.99-1.16)	**1.10 (1.08-1.12)**
Hospital Level			
1	**0.88 (0.85-0.91)**	0.98 (0.93-1.05)	**1.27 (1.25-1.28)**
2	**0.95 (0.92-0.98)**	**0.83 (0.79-0.87)**	**1.16 (1.15-1.18)**
3	REF	REF	REF
Length of Stay at delivery			
1-2 days	REF	REF	REF
3-4 days	**1.26 (1.22-1.31)**	**1.21 (1.14-1.28)**	**1.08 (1.07-1.10)**
5+ days	**1.56 (1.48-1.65)**	**1.40 (1.28-1.54)**	**1.18 (1.16-1.21)**
Delivery Year			
2002-2003	REF	REF	REF
2004-2005	**0.94 (0.91-0.98)**	**0.88 (0.82-0.94)**	**1.02 (1.003-1.03)**
2006-2007	0.96 (0.92-1.003)	**0.87 (0.82-0.94)**	**1.09 (1.07-1.10)**
2008-2009	0.96 (0.92-1.001)	**0.86 (0.80-0.92)**	**1.11 (1.09-1.13)**
2010-2011	**0.95 (0.91-0.99)**	**0.88 (0.82-0.94)**	**1.07 (1.06-1.09)**

[1]Also adjusted for SMM
Bold: $p<0.05$

Appendix B

Risk of Rehospitalization by Severe Maternal Morbidity at Delivery and Mental Health Indicators, Deliveries to MA Women 2002-2011

Depression and SMM Variables

Hospital Discharge:

Variable categorization	6 week HD aRR[1] (95% CI)	1 year HD aRR[1] (95% CI)
No SMM, no Depression	REF	REF
SMM, no Depression	**2.36 (2.11-2.64)**	**2.02 (1.86-2.19)**
No SMM, Depression	**1.33 (1.20-1.48)**	**1.51 (1.43-1.61)**
SMM, Depression	1.28 (0.69-2.35)	**1.78 (1.29-4.46)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, other chronic conditions
Bold: $p<0.05$

Observational Stay:

Variable categorization	6 week OS aRR[1] (95% CI)	1 year OS aRR[1] (95% CI)
No SMM, no Depression	REF	REF
SMM, no Depression	**2.23 (1.77-2.80)**	**1.63 (1.40-1.91)**
No SMM, Depression	**1.53 (1.27-1.84)**	**1.50 (1.35-1.66)**
SMM, Depression	**3.60 (1.71-7.56)**	1.69 (0.91-3.10)

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, other chronic conditions
Bold: $p<0.05$

Emergency Department:

Variable categorization	6 week ED aRR[1] (95% CI)	1 year ED aRR[1] (95% CI)
No SMM, no Depression	REF	REF
SMM, no Depression	**1.44 (1.31-1.57)**	**1.17 (1.12-1.22)**
No SMM, Depression	**1.34 (1.27-1.41)**	**1.27 (1.24-1.29)**
SMM, Depression	**2.09 (1.58-2.75)**	**1.42 (1.24-1.63)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, other chronic conditions
Bold: $p<0.05$

Substance Abuse and SMM Variables

Hospital Discharge:

Variable categorization	6 week HD aRR[1] (95% CI)	1 year HD aRR[1] (95% CI)
No SMM, no Substance Abuse	REF	REF
SMM, no Substance Abuse	**2.26 (2.02-2.53)**	**1.98 (1.83-2.15)**
No SMM, Substance Abuse	**1.43 (1.24-1.65)**	**2.01 (1.87-2.16)**
SMM, Substance Abuse	**3.84 (1.86-2.74)**	**2.87 (2.06-3.99)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, other chronic conditions
Bold: p<0.05

Observational Stay/Hospital Discharge:

Variable categorization	6 week HDOS[1] aRR[2] (95% CI)	1 year HDOS aRR[2] (95% CI)
No SMM, no Substance Abuse	REF	REF
SMM, no Substance Abuse	**2.26 (2.04-2.50)**	**1.85 (1.72-1.99)**
No SMM, Substance Abuse	**1.41 (1.24-1.61)**	**1.82 (1.70-1.94)**
SMM, Substance Abuse	**3.15 (1.93-5.15)**	**2.39 (1.73-3.29)**

[1]OS model on its own did not converge for OS 6 weeks
[2]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, other chronic conditions
Bold: p<0.05

Emergency Department:

Variable categorization	6 week ED aRR[1] (95% CI)	1 year ED aRR[1] (95% CI)
No SMM, no Substance Abuse	REF	REF
SMM, no Substance Abuse	**1.45 (1.33-1.58)**	**1.17 (1.13-1.22)**
No SMM, Substance Abuse	**1.47 (1.39-1.57)**	**1.28 (1.25-1.32)**
SMM, Substance Abuse	**2.16 (1.57-2.97)**	**1.37 (1.18-1.59)**

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy, other chronic conditions
Bold: p<0.05

Appendix C

Mediation of Chronic and Pregnancy-Associated Conditions and Rehospitalization by Severe Maternal Morbidity at Delivery, Deliveries to MA Women 2002-2011

Aim 3 Mediation Models
Hospital Discharge 6 weeks:

Main Exposure	Model 1: No Chronic Conditions aRR[1] (95% CI)	Model 2: No SMM aRR[1] (95% CI)	Model 3: SMM aRR[1] (95% CI)	Proportion of variable explained by SMM
SMM25	**2.24 (2.02-2.49)**	--	**2.27 (2.03-2.54)**	
Superimposed PE	--	**2.32 (1.92-2.82)**	**2.25 (1.85-2.73)**	3.0%
Severe preeclampsia	--	**1.90 (1.67-2.16)**	**1.79 (1.58-2.04)**	5.8%
Mild preeclampsia	--	**2.03 (1.84-2.24)**	**2.01 (1.82-2.22)**	1.0%
Chronic hypertension	--	**1.82 (1.62-2.05)**	**1.81 (1.61-2.04)**	0.5%
Gestational hypertension	--	**1.88 (1.83-2.04)**	**1.87 (1.72-2.03)**	0.5%
Pre-existing diabetes	--	**1.47 (1.29-1.68)**	**1.45 (1.27-1.66)**	1.4%
Gestational diabetes	--	**1.20 (1.10-1.30)**	**1.20 (1.11-1.30)**	0%
Asthma	--	**1.24 (1.12-1.36)**	**1.23 (1.12-1.36)**	0.8%
Substance abuse	--	**1.40 (1.22-1.61)**	**1.40 (1.22-1.61)**	0%
Depression	--	**1.29 (1.16-1.43)**	**1.29 (1.16-1.43)**	0%
Autoimmune disorders	--	**1.63 (1.35-1.96)**	**1.59 (1.32-1.91)**	2.5%

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: p<0.05

1 Year:

Main Exposure	Model 1: No Chronic Conditions aRR[1] (95% CI)	Model 2: No SMM aRR[1] (95% CI)	Model 3: SMM aRR[1] (95% CI)	Proportion of variable explained by SMM
SMM25	**1.94 (1.80-2.09)**	--	**1.95 (1.80-2.11)**	
Superimposed PE	--	**1.86 (1.62-2.14)**	**1.82 (1.58-2.09)**	2.2%
Severe preeclampsia	--	**1.48 (1.35-1.63)**	**1.43 (1.30-1.57)**	3.4%
Mild preeclampsia	--	**1.51 (1.40-1.62)**	**1.50 (1.39-1.61)**	0.7%
Chronic hypertension	--	**1.63 (1.50-1.76)**	**1.62 (1.50-1.75)**	0.6%
Gestational hypertension	--	**1.44 (1.36-1.53)**	**1.44 (1.36-1.53)**	0%
Pre-existing diabetes	--	**1.67 (1.53-1.81)**	**1.66 (1.52-1.80)**	0.6%
Gestational diabetes	--	**1.20 (1.13-1.26)**	**1.20 (1.14-2.27)**	0%
Asthma	--	**1.34 (1.27-1.42)**	**1.34 (1.26-1.42)**	0%
Substance abuse	--	**1.89 (1.76-2.03)**	**1.89 (1.76-2.03)**	0%
Depression	--	**1.49 (1.40-1.58)**	**1.49 (1.40-1.58)**	0%
Autoimmune disorders	--	**2.14 (1.93-2.37)**	**2.11 (1.90-2.34)**	1.4%

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: p<0.05

Observational Stay 6 weeks:

Main Exposure	Model 1: No Chronic Conditions aRR[1] (95% CI)	Model 2: No SMM aRR[1] (95% CI)	Model 3: SMM aRR[1] (95% CI)	Proportion of variable explained by SMM
SMM25	**2.39 (1.95-2.92)**	--	**2.24 (1.79-2.79)**	
Superimposed PE	--	**2.62 (1.79-3.84)**	**2.56 (1.75-3.74)**	2.3%
Severe preeclampsia	--	**2.17 (1.70-2.78)**	**2.06 (1.61-2.65)**	5.1%
Mild preeclampsia	--	**2.52 (2.11-3.01)**	**2.50 (2.10-2.98)**	0.8%
Chronic hypertension	--	**2.55 (2.11-3.10)**	**2.54 (2.10-3.08)**	0.4%
Gestational hypertension	--	**2.11 (1.82-2.44)**	**2.11 (1.82-2.44)**	0%
Pre-existing diabetes	--	1.10 (0.83-1.45)	1.09 (0.82-1.44)	0.9%
Gestational diabetes	--	**1.25 (1.07-1.45)**	**1.25 (1.08-1.45)**	0%
Asthma	--	**1.44 (1.22-1.70)**	**1.43 (1.21-1.70)**	0.7%
Substance abuse	--	1.31 (0.99-1.72)	1.30 (0.99-1.72)	0.8%
Depression	--	**1.54 (1.29-1.84)**	**1.54 (1.28-1.84)**	0%
Autoimmune disorders	--	1.07 (0.72-1.61)	1.05 (0.70-1.57)	1.9%

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: p<0.05

Observational Stay 1 year:

Main Exposure	Model 1: No Chronic Conditions aRR[1] (95% CI)	Model 2: No SMM aRR[1] (95% CI)	Model 3: SMM aRR[1] (95% CI)	Proportion of variable explained by SMM
SMM25	**1.69 (1.47-1.94)**	--	**1.59 (1.37-1.86)**	
Superimposed PE	--	**1.97 (1.55-2.51)**	**1.94 (1.53-2.47)**	1.5%
Severe preeclampsia	--	**1.53 (1.30-1.80)**	**1.49 (1.26-1.75)**	2.6%
Mild preeclampsia	--	**1.74 (1.54-1.95)**	**1.73 (1.54-1.94)**	0.6%
Chronic hypertension	--	**1.99 (1.76-2.25)**	**1.98 (1.76-2.24)**	0.5%
Gestational hypertension	--	**1.65 (1.50-1.81)**	**1.65 (1.50-1.81)**	0%
Pre-existing diabetes	--	**1.59 (1.37-1.83)**	**1.58 (1.37-1.83)**	0.6%
Gestational diabetes	--	**1.38 (1.27-1.50)**	**1.38 (1.27-1.51)**	0%
Asthma	--	**1.48 (1.35-1.63)**	**1.48 (1.35-1.62)**	0%
Substance abuse	--	**1.33 (1.15-1.54)**	**1.33 (1.15-1.54)**	0%
Depression	--	**1.49 (1.34-1.65)**	**1.48 (1.34-1.64)**	0.7%
Autoimmune disorders	--	**1.73 (1.43-2.10)**	**1.71 (1.41-2.08)**	1.2%

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: p<0.05

Emergency Department 6 weeks:

Main Exposure	Model 1: No Chronic Conditions aRR[1] (95% CI)	Model 2: No SMM aRR[1] (95% CI)	Model 3: SMM aRR[1] (95% CI)	Proportion of variable explained by SMM
SMM25	**1.42 (1.31-1.53)**	--	**1.45 (1.33-1.57)**	
Superimposed PE	--	**1.28 (1.08-1.52)**	**1.27 (1.07-1.50)**	0.8%

Severe preeclampsia	--	**1.26 (1.14-1.38)**	**1.23 (1.12-1.35)**	2.4%
Mild preeclampsia	--	**1.18 (1.10-1.26)**	**1.17 (1.09-1.26)**	0.8%
Chronic hypertension	--	**1.28 (1.17-1.39)**	**1.27 (1.17-1.38)**	0.8%
Gestational hypertension	--	**1.14 (1.08-1.21)**	**1.14 (1.08-1.21)**	0%
Pre-existing diabetes	--	**1.16 (1.06-1.28)**	**1.16 (1.05-1.28)**	0%
Gestational diabetes	--	**1.15 (1.10-1.21**	**1.15 (1.10-1.21)**	0%
Asthma	--	**1.34 (1.28-1.41)**	**1.34 (1.27-1.41)**	0%
Substance abuse	--	**1.43 (1.35-1.52)**	**1.43 (1.35-1.52)**	0%
Depression	--	**1.34 (1.27-1.42)**	**1.34 (1.27-1.41)**	0%
Autoimmune disorders	--	**1.29 (1.14-1.46)**	**1.28 (1.13-1.45)**	0.8%

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: p<0.05

Emergency Department 1 year:

Main Exposure	Model 1: No Chronic Conditions aRR (95% CI)	Model 2: No SMM (aRR 95% CI)	Model 3: SMM aRR (95% CI)	Proportion of variable explained by SMM
SMM25	**1.17 (1.13-1.21)**	--	**1.16 (1.12-1.21)**	
Superimposed PE	--	**1.21 (1.12-1.30)**	**1.20 (1.11-1.29)**	0.8%
Severe preeclampsia	--	**1.09 (1.04-1.13)**	**1.08 (1.03-1.12)**	0.9%
Mild preeclampsia	--	**1.10 (1.07-1.14)**	**1.10 (1.07-1.14)**	0%
Chronic hypertension	--	**1.22 (1.17-1.26)**	**1.22 (1.17-1.26)**	0%
Gestational hypertension	--	**1.09 (1.07-1.12)**	**1.09 (1.07-1.12)**	0%
Pre-existing diabetes	--	**1.20 (1.15-1.25)**	**1.20 (1.15-1.25)**	0%
Gestational diabetes	--	**1.12 (1.10-1.15)**	**1.12 (1.10-1.15)**	0%
Asthma	--	**1.30 (1.27-1.33)**	**1.30 (1.27-1.33)**	0%
Substance abuse	--	**1.25 (1.22-1.28)**	**1.25 (1.22-1.28)**	0%
Depression	--	**1.27 (1.24-1.29)**	**1.27 (1.24-1.29)**	0%
Autoimmune disorders	--	**1.31 (1.24-1.38)**	**1.30 (1.24-1.38)**	0.8%

[1]Adjusted for: age, race/ethnicity, education, method of delivery, insurance payer, plurality, length of stay at delivery hospitalization, prenatal care, year, hospital level, parity, marital status, cigarette smoking during pregnancy
Bold: p<0.05

Curriculum Vitae

ELIZABETH M. HARVEY
137 Mount Auburn Street, Unit 1, Cambridge, MA 02138
Phone: (609) 731-2105 • Email: eharve15@jhu.edu

EDUCATION

Ph.D. Candidate	2012-present	JOHNS HOPKINS BLOOMBERG SCHOOL OF PUBLIC HEALTH Department of Population, Family and Reproductive Health
M.P.H.	2010	UNIVERSITY OF NORTH CAROLINA GILLINGS SCHOOL OF GLOBAL PUBLIC HEALTH Department of Maternal and Child Health
A.B.	2006	PRINCETON UNIVERSITY History of Science

ACADEMIC EXPERIENCE

RESEARCH

JOHNS HOPKINS BLOOMBERG SCHOOL OF PUBLIC HEALTH
2013-present
Department of Population, Family and Reproductive Health, Research Assistant

- Abstracted and analyzed low birth weight deliveries at Mercy Medical Center in Baltimore to improve maternal and infant outcomes and engaged in data translation with Baltimore City Health Department to educate providers
- Evaluated referral services for parents of children with autism, epilepsy, and seizure disorders in collaboration with Maryland Department of Health and Mental Hygiene (DHMH)
- Investigated implementation of Maryland legislative policy of Medical Orders of Life Sustaining Treatment (MOLST) in the Neonatal Intensive Care Unit (NICU) at Johns Hopkins Hospital; created study design and led data analysis for collaborative study of life sustaining treatment orders for pediatric patients in Oregon

UNIVERSITY OF NORTH CAROLINA GILLINGS SCHOOL OF GLOBAL PUBLIC HEALTH
2009- 2010
Department of Maternal and Child Health, Research Assistant

- Assisted Principal Investigator and Project Manager with Longitudinal Study on Child Abuse and Neglect
- Managed study participants and conducted case record reviews throughout North Carolina Departments of Social Services using child maltreatment coding instruments (NIS-2 and MMCS)
- Conducted literature reviews on child maltreatment and adverse childhood experiences

TEACHING

JOHNS HOPKINS BLOOMBERG SCHOOL OF PUBLIC HEALTH
Department of Population, Family and Reproductive Health, Teaching Assistant

- 380.662.01 Critiquing the Research Literature in Maternal, Neonatal and Reproductive Health, 2014

- 380.765.81 Preventing Infant Mortality and Promoting the Health of Women, Infants and Children, 2014

PROFESSIONAL EXPERIENCE

MASSACHUSETTS DEPARTMENT OF PUBLIC HEALTH
Boston, MA
Bureau of Family Health and Nutrition
September 2014-present
Technical Advisor, Graduate Student Intern

- Data lead for cost effectiveness analysis for Project LAUNCH, a model of integrated behavioral health and pediatric primary care in Boston
- Co-led Needs Assessments for Early Childhood Comprehensive Systems grant and Massachusetts Infant and Early Childhood Home Visiting grant
- Evaluation team member for Welcome Family, a pilot program for universal one-time home visit for families in Massachusetts
- Co-led Child and Adolescent Work Group to identify statewide health priorities for the 2015 Massachusetts Title V Maternal and Child Health Block Grant Needs Assessment
- Analyzed available statewide youth health data and designed Massachusetts Youth Health Priorities Survey
- Conducted and analyzed key informant interviews and focus groups

BOSTON PUBLIC HEALTH COMMISSION
Boston, MA
Bureau of Child, Adolescent and Family Health
June-August 2013
Graduate Research Assistant

- Provided technical assistance on examining racial/ethnic disparities in birth outcomes through a Perinatal Periods of Risk (PPOR) study among Boston, MA infants

MASSACHUSETTS DEPARTMENT OF PUBLIC HEALTH
Boston, MA
Bureau of Family Health and Nutrition, Office of Data Translation
2010- 2012
CDC/CSTE Applied Epidemiology Fellow

- Coordinated the implementation of the statewide Review of Infant Mortality Program, an initiative of the Medical Director to perform surveillance of infant deaths and in-depth case reviews
- Analyzed ten years of Massachusetts (MA) infant mortality data by socio-demographic maternal and infant characteristics, geography, and community-level systems to determine trends and departmental priorities
- Facilitated internal and external agreements to acquire more timely infant birth and death records and District Attorney authority to obtain medical records for reviewable cases
- Co-Lead for the Boston Action Learning Collaborative: Partnership to Eliminate Disparities in Infant Mortality, assessing how racism affects perinatal health outcomes among Boston residents
- Co-Data Lead for MA on the Maternal, Infant, and Early Childhood Home Visiting grant; assisted in preparing application securing $40 million over five years

LOS ANGELES COUNTY DEPARTMENT OF PUBLIC HEALTH
Los Angeles, CA

Graduate Student Internship Program, Maternal and Child Health Bureau
Research, Evaluation, and Planning Intern, Maternal, Child, and Adolescent Health
May-August 2009

- Compiled and analyzed county perinatal indicator data for the 2007 Family Health Outcomes Project using SAS 9.2 and MapInfo software
- Completed executive projects on: 1) the rise of infant mortality in rural areas of the county and 2) the decrease in early entry into prenatal care in the entire county

NEW ALTERNATIVES FOR CHILDREN, INC.
New York, NY
Case Associate in Foster Care and Adoption, Princeton Project 55 Fellow
2006- 2008

- Conducted and documented foster home, school, and family visits at social service agency focused on children with special medical needs
- As person responsible for the submission and appeals of all foster parent financial subsidy applications, streamlined application and reporting process
- Co-led weekly tutoring group and siblings of children with disabilities group
- Planned and evaluated agency-wide annual special Olympics

EDITORIAL ACTIVITIES

MATERNAL AND CHILD HEALTH JOURNAL
Peer Reviewer
2013-present

PRESENTATIONS

ORAL PRESENTATIONS
Maternal Hypertensive Disorders, Chronic Conditions and Severe Maternal Morbidity at Delivery, Massachusetts 2000-2012
Maternal and Child Health Epidemiology Annual Conference, September 2016

Severe maternal morbidity at delivery and one year postpartum hospital encounters, Massachusetts deliveries 2002-2011
Maternal and Child Health Epidemiology Annual Conference, September 2016

Precursors to Adverse Pregnancy Outcomes in Severely Premature Deliveries: An Examination of Antenatal Hospitalizations, Massachusetts 2002-2008
Council of State and Territorial Epidemiologists Annual Conference, June 2012

A Closer Look at Infant Deaths due to Prematurity: Variation in Receipt of Antenatal Corticosteroids, Massachusetts 2002-2008
Council of State and Territorial Epidemiologists Annual Conference, June 2012

Infant Mortality as a Measure of Perinatal Health
Tufts University MPH Class on Maternal and Child Health Policy Invited Lecturer, September 2011

Evaluation of Maternal Smoking Surveillance Systems in Massachusetts
Council of State and Territorial Epidemiologists Annual Conference, June 2011
Council of State and Territorial Epidemiologists Fellowship Training Invited Speaker, August 2011

Child Maltreatment and Post-Secondary Educational Enrollment and Attainment
Maternal and Child Health Epidemiology Annual Conference, December 2010

POSTER PRESENTATIONS
Maternal Hypertensive Disorders, Chronic Conditions and Severe Maternal Morbidity at Delivery, Massachusetts 2000-2012
9th Annual Women's Health Research Symposium, Johns Hopkins Bloomberg School of Public Health, May 2016

An Investigation of Low Birth Weight, Mercy Medical Center, Baltimore, MD, 2010-2011
American Public Health Association Annual Meeting, October 2015
Delta Omega Poster Competition, Johns Hopkins Bloomberg School of Public Health, February 2015

Decreasing Infants Deaths due to Prematurity in Practice: Eligibility and Receipt of Antenatal Corticosteroids, Massachusetts 2000-2008
Maternal and Child Health Epidemiology Annual Conference, December 2011

Is unintended pregnancy associated with physical violence by an intimate partner during pregnancy?
Maternal and Child Health Epidemiology Annual Conference, December 2009

PUBLICATIONS
Harvey EM, Strobino D, Sherrod L, Webb MC, Anderson C, White JA, Atlas R. Community-Academic Partnership to Investigate Low Birth Weight Deliveries and Improve Maternal and Infant Outcomes at a Baltimore City Hospital. Maternal and Child Health Journal. 2016 Jul 26:1-7.

Braid S, **Harvey EM**, Bernstein J, Matoba N. Early introduction of complementary foods in preterm infants. Journal of pediatric gastroenterology and nutrition. 2015 Jun 1;60(6):811-8.

Lu E, Dayalu R, Diop H, **Harvey EM,** Manning SE, Uzogara SG. Weight and mental health status in Massachusetts, National Survey of Children's Health, 2007. Matern Child Health J 2012;16 Suppl 2:278-86

Flaherty EG, Thompson R, Dubowitz H, **Harvey EM,** English DJ, Proctor LJ, et al. Adverse childhood experiences and child health in early adolescence. JAMA Pediatr 2013;167(7):622-9.

HONORS AND AWARDS
2015-2016: HRSA Maternal and Child Health Epidemiology Training Fellowship
2012-2016: Maternal and Child Health Training Grant, Johns Hopkins Bloomberg School of Public Health
2016: 1st Place Poster Award, 9th Annual Women's Health Research Symposium, Johns Hopkins Bloomberg School of Public Health
2015: American Public Health Association Maternal and Child Health Student Fellow
2015: Health Resources and Services Administration Trainee Fellowship
2015: 2nd Place Poster Award, Delta Omega Poster Competition, Johns Hopkins Bloomberg School of Public Health
2014: John and Alice Chenoweth-Pate Award, Johns Hopkins Bloomberg School of Public Health

2014-2015: Odd Fellows Academic Grant, Home for Orphans of Odd Fellows of Pennsylvania
2012-2013: Robertson Award, Johns Hopkins Bloomberg School of Public Health
2010: 1st Place Abstract, Maternal and Child Health Epidemiology Conference
2009: Graduate Student Internship Award, UNC Gillings School of Global Public Health
2006: Princeton AlumniCorps Project 55 Fellowship
2004-2006: USA Rugby All-American Collegiate Team Selection

LEADERSHIP AND SERVICE
2014-2016: Johns Hopkins Bloomberg School of Public Health, Doctoral Committee Student Representative
2013-2014: Johns Hopkins Bloomberg School of Public Health, Departmental Student Association Co-President
2011-2012: Princeton AlumniCorps Boston Area Committee, Chair
2004-2006: Princeton University Women's Rugby Team, Co-Captain

SKILLS
- Microsoft Office
- SAS 9.2 Programmer, Intermediate/Advanced Programmer
- STATA/SE 12, Intermediate Programmer
- SUDAAN 10.0, Intermediate Programmer
- R, Beginner Programmer
- ArcGIS, MapInfo, Joinpoint
- EndNote, RefWorks
- Proficient in Spanish and studied in Spanish-speaking countries